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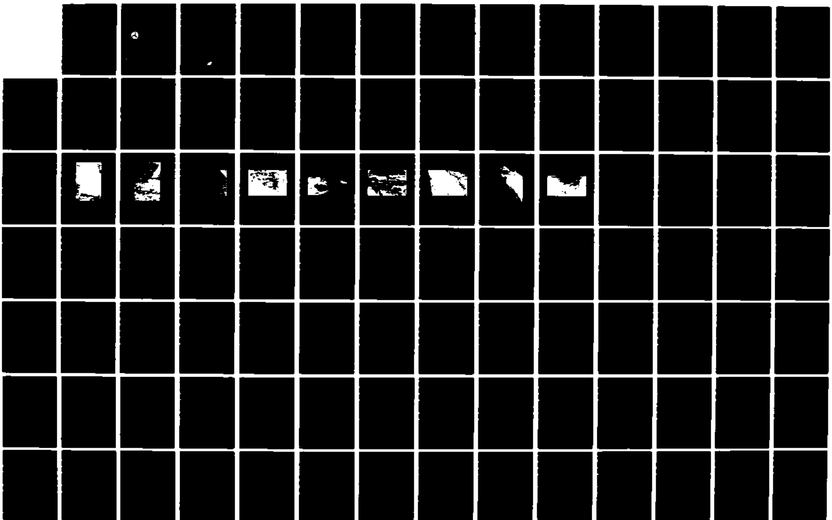

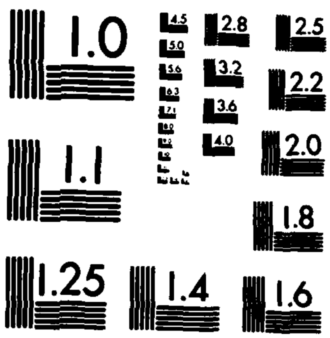

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A FIELD GUIDE FOR ARCTIC OIL SPILL BEHAVIOR

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U.S. Coast Guard
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NOTICE

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16. Abstract

A Field Guide for Oil Spill Behavior was developed to provide the On-Scene Coordinator (OSC) with the spill behavior information needed to assess whether timely and adequate containment and removal actions are taken. The field guide describes arctic ice conditions, the physical properties of oil as it weathers, oil spill behavior in cold water and ice conditions, and spill retention potential for the Alaskan shore line. The guide then uses six spill scenarios to show the user how to apply spill behavior information to solve real world problems. Additional keywords: Beaufort Sea oil weathering, [illegible], evaporation, [illegible] [illegible]ions, combustibility, [illegible]tion [illegible] shores, [illegible].

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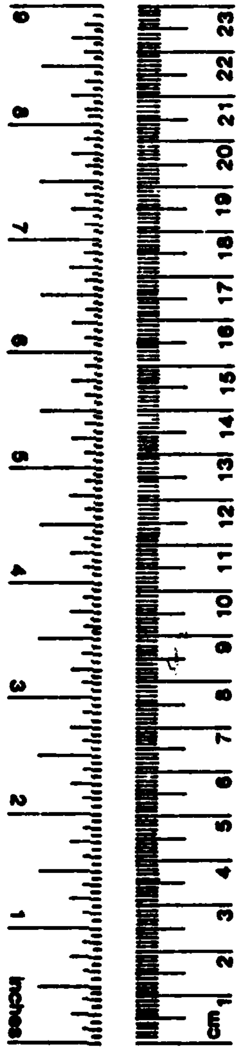
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

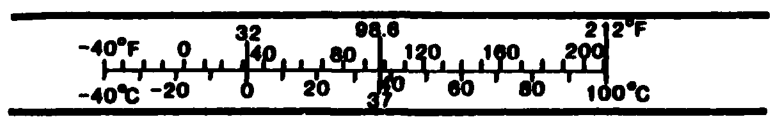
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Special recognition goes to Professor Dag Nummedal of Louisiana State University, who developed the spill Retention Index for the Alaskan Beaufort Sea coast. The value of this work to the Coast Guard Field Guide cannot be overstated. We are indebted to Professor Nummedal and his team, who worked for two summers on the Beaufort Sea coast, for providing one of the most important tools that will be available to the On Scene Coordinator. Professor Nummedal was especially helpful in providing this project with the originals of his coastal charts showing Retention Index. These charts are presented in Section 4 in exactly the same form as they appeared in the original NOAA study.

We would also like to thank Mr. J.A. Whittick of the Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, for permission to use the pictures of the KURDISTAN spill that appear in Section 3 of this report.

Finally, we would like to thank Lucy Merrill for her long hours of work in editing, typing, and proof reading the final manuscript.

INTRODUCTION

The Field Guide for Oil Spill Behavior was developed to provide the On-Scene Coordinator (OSC) with quick and easy access to spill behavior information, so that he can quickly assess the threat of an oil spill to the environment and plan for effective response action. The Field Guide is designed to answer three questions that determine how the response effort will be applied:

o What is the nature of the oil as it weathers? This determines the kinds of equipment that would be suitable for clean-up.

o How does the oil spread in the environment? The OSC needs to know if the spreading is likely to be extensive or if it is confined to a relatively limited area.

o How does the oil move as it is released from the ice? The OSC needs to know where the oil will go and how long it is likely to be retained on the shoreline.

These are the important issues for the OSC and the questions that this Field Guide addresses.

The general plan for developing this information was to:

o Describe ice conditions in the Alaskan Arctic

o Describe the physical properties of oil as it weathers

o Describe oil spill behavior in an arctic environment

o Predict the likely persistence of spilled oil on the Alaskan shoreline

o Illustrate how to use the information presented in the other sections in a set of oil spill scenarios.

The goal was to produce a book that is easy to use and designed for rapid problem solving under the most difficult operational conditions.

This introduction is not intended to summarize the contents of the Field Guide, rather it is intended to provide some background on each section. The paragraphs offer comments on the sections of the Field Guide.

Ice Conditions. This section provides a description of the ice conditions that can be expected in the Alaskan Beaufort Sea in each season. This section should be very helpful to persons who are new to the Arctic, and a good source of review of information to those who are old arctic hands. In all cases, however, it must be emphasized that this is background information. Ice conditions vary radically from season to season and even between areas. As a result, it is important that the OSC observe, measure, and record the ice conditions at the spill site. These are the ice conditions that will influence spill behavior and they could be far different from what may be considered as normal for the area. Appendix A contains a list of commonly used ice terms.

Weathering of Oil. It is important to know what the oil is like in order to plan the best response. This section uses a set of physical properties to describe the condition of the oil. These physical properties were calculated from mathematical models developed over a period of many years by Don Mackay at the University of Toronto. Although there has been no on-site testing of the model in the Alaskan Beaufort Sea, winter weathering tests were conducted at the Coast Guard R & D Center at Groton, Connecticut and the results of these tests were used to refine the models. In short, these models have been used to develop the best graphical records of oil weathering

in a winter environment that are available. For this text, the models are the source of easy-to-use graphs that show evaporation, and changes in viscosity and pour point as the oil is exposed in the environment. Evaporation is important because this represents the largest loss of oil to the environment. Viscosity and pour point describe physical characteristics that are important in planning the recovery effort. Taken together, the physical properties of the spilled oil establish the spill response requirements.

Arctic Oil Spill Behavior. This section describes how the spilled oil spreads and interacts with the environment. In some cases, it describes how the oil is altered in the environment. The reader should take note of the careful choice of words used in dealing with this subject. We "describe" how the oil responds in the arctic environment, and that is the best we can do. There are some equations and graphs that help to describe spill behavior in the environment; however, the way in which oil responds in an ice environment is extremely complicated and it is not presently well represented by any mathematical model. A great many laboratory and field tests have been performed that help to describe spill behavior in ice, and although the results of these tests do not all agree in every detail, there is still a remarkable similarity in results that at least establish trends and limits of oil spill behavior. These limits should be entirely adequate to permit the OSC to determine what a spill can be expected to do and what action should be taken to prevent environmental damage.

Oil Interaction With the Shoreline. In the event of an oil spill in the American Beaufort Sea or on its shoreline, the Coast Guard predesignated OSC is responsible for ensuring that timely and adequate containment and removal actions are taken. In most cases, especially in this region, responsible parties will probably take the appropriate cleanup action and the Coast Guard OSC's role will be to monitor these actions. If the responsible party's actions are non-existant or inadequate, or when the responsible party is unknown, the OSC may initiate cleanup action using Federal pollution funds. In either case, the OSC will be operating in a unique, remote, and hostile envrionment, where cleanup actions are expensive and environmental conditions are very sensitive.

The most immediate concern is to protect highly sensitive environmental areas that are threatened by the spill. Taking this action involves two elements: 1) knowing where the sensitive areas are, and 2) being able to determine if the spilled oil threatens these areas. This section identifies where the sensitive areas are.

Several years ago the National Oceanic and Atmospheric Administration (NOAA) sponsored a project to survey the entire Alaskan Beaufort Sea coastline to evaluate shoreline types according to spill retention potential. During the summers of 1977 and 1978 a scientific team sampled, photographed, and described the entire Alaskan coast from Pt. Barrow on the west to Demarcation Point in the east. Beach samples were taken 5 miles apart over the entire coast. The team also obtained nearly continuous oblique aerial photography that was annotated with detailed descriptions. This information was evaluated to determine the spill retention potential for each coastline type and the results were plotted on a series of 30 charts. These charts are included in this Field Guide and provide the basis for evaluating potential spill impact on the entire Alaskan Beaufort Sea coastline.

Oil Spill Scenarios. The final section of the Field Guide presents a set of six oil spill scenarios that are used to show how to use the information contained in the Field Guide to solve real world oil spill behavior problems. This section of the Field Guide is intended to be used as a working handbook. It contains a set of eleven work sheets to record spill behavior data and a complete set of instructions on how to use the sheets and the information contained in the other sections of the Field Guide to solve behavior problems. It is intended that these Work Sheets be used by the OSC and his staff to plot the extent of the spill, predict how it will spread, and estimate how it will move when it is released by the ice.

To make the scenarios as realistic as possible, they were set in typical places where the petroleum development activities described could occur. The selection of these scenarios does not imply that the development activities described are in any way hazardous or involve an unusually high risk of a spill. Further, the spill locations were not selected to illustrate spill types or spill locations that would be particularly hazardous to the environment. The scenarios were simply selected to illustrate typical spill behavior situations.

The scenarios, however, do not avoid suggesting that an offshore spill could result in a risk of environmental damage. The spill behavior problems are extended to the point that the oil released reaches the shoreline, and when it does there is an evaluation of potential impact. This is part of the description of the process that must be used to trace the complete spill behavior problem. It is definitely not intended, however, that these scenarios should be used to identify a problem or to argue against a particular type or location for development. The Field Guide is designed to assist OSC in responding to an oil spill, not to advocate a particular course of action.

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1.0 ICE CONDITIONS

The following sections are arranged to give the user a concise but complete survey of ice conditions along the Beaufort Sea coast of Alaska. The different ice types are described beginning with the period of least ice motion and maximum ice thickness. Then the seasonal changes are followed through the year taking the reader back to the period of stable ice conditions. A separate section describes the important topics of ice movement and deformation together with the relationship between sea ice and weather.

Photographs of the major ice types and forms are included at the end of this section. Rather than arrange them alphabetically or as mentioned in the text, the photographs are arranged by season beginning with the shorefast ice season and continuing through break-up, summer, and fall. The photos included are as follows:

Season	Figure Number
Shorefast ice	1.1
Break-up	1.2, 1.3, 1.4, 1.5
Summer	1.6
Fall	1.7, 1.8, 1.9, 1.10

Most of the photographs cover the seasons in which the nearshore areas are most dynamic--break-up and fall. During the summer nearshore areas usually contain little ice and during the shorefast ice season the ice does not change much in appearance, therefore only two photos of these seasons are included. Arrows on the photos are used to point out special ice features mentioned in the titles.

1.1 Shorefast Ice Season

Stable, shorefast ice characterizes this season. Shorefast ice is defined as first-year ice that is attached to the shore (Figure 1.1). In shallow water the ice is frozen to the sea floor. Often multi-year floes may be incorporated into the shorefast ice if the floes are relatively near shore during freezeup. The shorefast ice varies in extent during the season but it always retains the property of being virtually immobile. The shorefast ice season usually begins around late November but there is considerable yearly variation. For example, in some years the nearshore new ice becomes stable in late October, but in other years significant ice motions can still occur in December. The shorefast ice season generally ends in late May as the break-up process begins.

Shorefast ice grows according to a fairly regular pattern. Sheltered areas are always the first to develop shorefast ice and the ice grows seaward as it thickens. The ice thickens at a rate of about 10 mm per day through February. Later growth proceeds more slowly so that ice reaches an average maximum thickness of 1.7 to 2 meters in early May.

The seaward growth is not as regular. Forces generated by the wind and currents can break away large pieces of shorefast ice, and interactions with the pack ice can change the boundary of the stable ice by deforming the seaward edge. These deformations reduce the extent of the shorefast ice by creating shear ridges and rubble.

Shorefast ice grows seaward during the winter and reaches its maximum extent in April of most years. Typically, the outer edge of shorefast ice is bounded by shear ridges in about 18 meters of water. During years of intense pack ice pressure, the shorefast ice may be limited to a narrower offshore area, especially

near headlands and points where the stable ice may only reach to the 6 or 12 meter isobath. In other years, the landfast ice may reach to the 20 meter isobath and beyond if the pack ice does not impact the seaward edge. This extreme seaward growth of land fast ice occurs seaward of the shear zone. When the pack ice reapplies shearing forces, or when a storm surge changes sea level, the floating fast ice seaward of the grounded ridges is likely to move.

Surface features of the shorefast ice sheet do not have much vertical development, generally less than 30 centimeters. Most, if not all, of the surface features are caused by early season deformation. Thin ice is easily moved and deformed by the wind, causing ridges only a few to 30 centimeters high to be formed. Rafting is common as one ice sheet overrides another and leaves a "micro ridge" only a few centimeters high on the surface (Figure 1.9E).

Sometimes the new ice does not remain in a flat sheet. Wind or wave action breaks thin ice into many pieces. As the pieces bump and rub together they form small round floes called pancake ice (Figure 1.7). Pancake ice can be identified by the tiny, round ridges on the perimeter of each floe that are preserved as the season progresses.

Taller features are also found in the shorefast ice and are commonly associated with an old shear zone or with multi-year ice pieces. Multiple sets of shear ridges are often formed over the course of a winter. The shorefast ice grows seaward until it interacts with the pack ice. This interaction forms shear ridges (Figure 1.3B) that protect the remaining shorefast ice from deformation because they are grounded. The next time the pack retreats from the edge of the shorefast ice, new ice becomes attached to the shear ridges. This new ice can then become part of the shorefast ice sheet and have a new, active set of shear ridges at its seaward boundary. This process continues until the pack ice prevents the further expansion of the shorefast ice. Generally the shear ridges that form later in the winter have more vertical development because the ice is thicker and the deforming forces are greater with increasing distance offshore.

Snow accumulates on all ice surfaces except for very smooth refrozen melt ponds and the upwind side of pressure ridges. The snow accumulates in drifts parallel to the wind leaving spaces between drifts covered by very little snow. Thicker snow acts as an insulator and inhibits ice growth. Thus, the shorefast ice develops a bottom topography of undulating troughs and ridges that correspond to the surface snow drifts. Section 3.4 describes these features and their potential for collecting oil spilled under ice.

In summary, new ice forms in the fall and becomes stable in late November. Nearshore ice becomes bottom fast during the winter as the ice becomes 1.7 to 2 meters thick. Floating shorefast ice is generally undeformed and has snow drifts aligned with the wind. Shear ridges formed in the early winter may be encountered shoreward of the final active set of shear ridges usually grounded in about 18 meters of water. During the winter, the shorefast ice is virtually immobile.

1.2 Shear or Stamuki Zone

The shear zone is a region of severely deformed sea ice that commonly forms at the seaward edge of the shorefast ice (Figure 1.3B). Mobile pack ice interacts with the stable shorefast ice causing the first-year ice to deform. The shearing component

of the pack ice motion, which is almost always present, results in the ice being rounded into very small pieces. Ridges that form as a result of shearing have one nearly vertical face and are linear rather than having the sinuous form of compression pressure ridges. This makes them easy to identify. In a strong shear ridging event, the pack ice may exert enough force to build ridges that reach downward to the sea floor and upward to a height of over 3 meters. Grounded ridges can resist the force of the pack ice and form a barrier that prevents deformation of the remaining shorefast ice. The deep and very irregular keels of the shear ridges may be an important barrier to oil spreading under the ice. Oil may also be trapped in spaces between the keels of ridges. Section 3.4.4 discusses the likely capacity of these large-scale under-ice features.

The exact location and extent of the shear zone across the Beaufort Sea coast varies from year to year. In some years deformation events begin early in the fall and shear ridges begin to form in water depths of 6 to 9 meters close to barrier islands and other boundaries such as headlands and nearshore shoals. As the season progresses, these early features are commonly made part of the shorefast ice because new first-year ice forms seaward. The next deformation event forms a new set of shear features some distance offshore of the earlier set. This process may continue until the last set of shear ridges form in about 18 to 21 meters of water. Depending upon the magnitude of the forces involved, none or most of the shear ridges may be grounded. Grounding occurs when the first-year ice is crushed and forced into the remaining shorefast ice. The broken ice piles above and below the level ice surface in a height to depth ratio of about 1 to 4 or 5; that is, grounded ridges in 18 meters of water may be about 4 meters high on the surface.

The shear ridge system may stretch from Barter Island to Barrow but never in a continuous, unbroken line. There are usually separate shear systems across the Beaufort Coast corresponding to particular water depths. The shear ridge lines are often broken where water depths change abruptly and where the presence of shoals and islands influence ice dynamics. Given the predominant easterly winds during the winter, shear ridges are most likely on the western side of bays and around points of land and islands exposed to ice movement from the east, such as Cross Island. Shear ridges are common on the north and eastern shores of barrier islands and headlands.

Grounded shear ridges have a stabilizing influence on the shorefast ice since they absorb the energy transmitted by the polar pack ice. Shear ridges are also important in that they are the only form of first-year ice likely to survive through the summer in an unusually cold year. Thus, any oil they trap may be held in these features and transported by them. If these ridges survive, they become fragmented and usually free floating by summer's end. These ridges are of limited extent, usually only a few hundred meters or less in length.

1.3 Polar Pack Ice

Most of the Beaufort Sea is covered by the Polar Pack. About 80 to 90 percent of this ice is multi-year ice (Figure 1.6) and about 10 to 20 percent first-year ice with most first-year ice occurring near the Beaufort coast. Multi-year ice is stronger and thicker than first-year ice; therefore, as the pack moves, the first-year ice is often crushed between multi-year floes. Sometimes the area covered by first-year ice may be small because

of complete deformation. This leaves 99 to 100 percent of the area covered by multi-year ice. The Polar Pack usually advances to within about 35 kilometers (19 nm) of the shore in fall and retreats in the summer to beyond the continental break. Extreme events have been recorded in which the pack impinges upon the Beaufort coast in summer or lies well over 90 kilometers (49 nm) offshore. In winter the pack is always close to the coastline.

Polar pack ice is composed of ice floes ranging from tens of meters to tens of kilometers in diameter. Many multi-year floes are several kilometers in diameter, 3 to 5 meters thick, and have an undulating surface (Figure 1.6) due to summertime weathering. Near the shear zone the polar pack ice moves westward as it responds to the Beaufort Sea gyral circulation. This average motion is commonly interrupted on time scales from days to a week or more by winds and/or currents from other directions often associated with storms. These forces may cause the ice to move in any direction for a short time, but generally the storms cause the ice to move to the east faster than the average summer drift, which is about 11 km (6 nm) per day.

1.4 Break-Up Ice Season

The break-up ice season usually begins during the last two weeks of May when the major rivers of the north slope region flood over the fast ice (Figure 1.2). Water absorbs much more shortwave solar radiation than ice. This accelerates the ice melting under the flooded areas. Since the ice surface is above sea level, any openings through the ice act as drains. Seal breathing holes or naturally occurring thin spots develop into major drainage points for water that has accumulated on the ice surface. Large whirlpools, called strudel zones, often develop as the water drains. These areas are dangerous to approach.

In early June the ice surface begins to melt and melt pools form because of the long daylight hours and rising temperatures. On undisturbed, flat shorefast ice, a shallow layer of water may develop stretching several kilometers or more in all directions. Water does not accumulate on ridged ice, and therefore ridges remain relatively dry and reflective (Figure 1.3B). After about three weeks, (at the end of June), the shorefast ice is usually decayed to the point that cracks develop and the previously stable ice begins to move (Figure 1.4). Floes many kilometers across have been observed during this time. The presence of open water greatly enhances the ocean's ability to absorb energy. The cracks quickly expand (Figure 1.5) and the remaining ice is then free to move with the wind. Floe size generally decreases as the break-up season progresses because the ice deforms and decays. By the end of July or beginning of August the shorefast ice is usually gone.

During the early stages of break-up the shear zone remains intact, especially if grounded features are present. The ridges resist decay since they are more reflective than the water covered ice (Figure 1.3B). The shear zone breaks up as the ridges melt away and the surrounding ice becomes mobile. Some of the more massive ridge fragments survive the break-up and summer seasons and become multi-year ice fragments. Usually the shear zone deteriorates rapidly in mid to late July as the ridges collapse and capsize.

In the polar pack ice, the first-year ice decays each year but generally lags behind the melt near shore by one to three weeks. Once the first-year ice begins to melt, the multi-year ice is free to move

in the light summer winds. Thus, open areas are likely to appear in the southern pack ice before all the shorefast ice has decayed. As melt water drains off ridges, collects in puddles (Figure 1.6A) and drains out of holes, the surfaces of multi-year floes develop a rounded appearance (Figure 1.6B). The individual blocks of ice that developed into ridges are no longer visible. Instead, the ridges now resemble rolling hills, the valleys between being refrozen melt ponds or gently sloping ice.

1.5 Summer Ice Season

The summer ice season begins after the shorefast ice has broken up and disappeared. This usually happens during late July or early August. Typically the summer ice season lasts about 60 days along the Beaufort Sea coast of Alaska. Any fragments of the shear zone or multi-year floes nearshore decay as the polar pack ice edge retreats north, usually through the middle of September. Open water conditions (less than about 10 percent ice cover) prevail from the coastline to about 30 to 65 kilometers (16 to 35 nm) from shore.

As mentioned previously, during exceptional years the edge of the polar pack ice may retreat to more than 90 kilometers (49 nm) from shore, or it may advance to the coastline eliminating open water areas. During the summer of 1975 a shoreward advance of the polar pack ice edge caused shipping along the North Slope to be virtually halted. Polar pack ice covered 30 to 60% of the normally open water area. In other years the edge of the pack ice may advance shoreward into open water areas on a smaller scale. In these cases a tongue of polar pack ice about 40 km (22 nm) long and 20 km (11 nm) wide advances to cover a relatively small percentage of the open water area. These ice invasions are often caused by single storms and last only about one or two weeks. Storms have been observed to propel multi-year floes exceeding one kilometer (0.5 nm) mile in diameter into nearshore areas.

The points to remember, then, are that in normal years light easterly winds are punctuated by a few weak storms bringing westerly winds for a day or two. In expectional years southerly winds may maintain large areas of open water or northerly winds may cause the pack ice to advance to the coast.

1.6 Fall Ice Season

The fall ice season occurs from freeze-up to the time that the shorefast ice becomes stable. Typically, freeze-up occurs during late September in sheltered waters along the Beaufort Sea coast. Calm, cold air accelerates freeze-up. The initial freeze may be followed by a warmer or windy period during which some or all the new ice is either melted or deformed. By the first or second week of October, the freeze-up process is usually well underway and substantial areas of new ice cover the coastline and stretch out into the protected waters of bays and inside the barrier islands. At this time, the polar pack ice moves toward the shore and large areas of new and young first-year ice occur along its advancing edge. Eventually the ice growing seaward and the ice moving toward shore meet and the first shear zone of the year is created.

New ice formation can occur in several ways. Depending upon environmental conditions, a smooth sheet of columnar ice can grow. Columnar ice crystals are oriented vertically with a 2:1 length to width ratio. They range from 0.5 to about 5 cm in length. Frazil ice grows in windy conditions with the water at its freezing point. Frazil ice

is composed of individual discs or particles of ice. The wind generates waves that mix the surface layers and cause frazil ice crystals to form below the surface. As the crystals rise to the surface, their orientation is random and further wind and wave action piles the ice unevenly in layers up to 15 cm thick. If snow falls into water whose temperature is near the freezing point, slush is formed. Frazil ice formation is also thought to contribute to slush accumulation.

As frazil ice crystals accumulate and coagulate, grease ice is formed on the surface. Grease ice does not reflect much light, and gives the sea a matte appearance. Later, shuga may form from the grease ice as the wind and waves cause the ice to form into spongy lumps a few centimeters across. Nilas is a term applied to thicker, elastic, smooth ice that bends on waves and swells and typically deforms under pressure, thrusting in a pattern of interlocking "fingers" (Figures 1.8A and 1.9A). Nilas reaches a maximum thickness of about 10 centimeters. As the ice continues to thicken, it is called young ice (Figure 1.9B), and when it becomes about 30 centimeters thick, it is referred to as first-year ice (Figure 1.9C). Several gradations of young and first year ice exist and are given in the glossary. Briefly, these gradations relate appearance to thickness: darker tones such as grey are thinner than grey-white.

Columnar ice growth can occur in the calm water once a strong layer of ice, such as nilas, exists. As the columnar crystals grow, they form plates of ice with the very saline water (brine) trapped between them. As the plates connect, these brine pockets are held in the ice sheet until the ice warms in the spring. When the ice melts, the brine pockets connect and drain out of the ice.

Fall season weather is important in determining the new ice growth and deformation. This season begins with subfreezing nighttime temperatures and the first ice forming during the typical subfreezing cold spell in September. By October the average daytime maximum temperatures are normally about $-6^{\circ}C$ ($21^{\circ}F$) and readings of $-20^{\circ}C$ ($-4^{\circ}F$) at night are not uncommon. Sea ice quickly forms on the ocean under these conditions if the wind is calm. Thin ice types, for the most part nilas, are easily deformed by moderate winds. However, calm or light wind periods usually occur only in between storms. In most years, storms are frequent in October and November. If the ocean is mostly free of ice cover, storm winds with speeds of over 30 meters per second (60 knots) can cause waves capable of breaking new ridges and other features that cannot bend sufficiently. Storms continue through November, and as the temperature falls during the day to below $-20^{\circ}C$ ($-4^{\circ}F$), ice forms on the ocean in all but the most intense wind storms. By the end of November, or in December, the nearshore ice becomes stable and the shorefast ice season begins.

The surface features of the new ice sheet depend upon the type of deformation processes that occurred as it was forming. Cold calm air provides ideal ice growing conditions, and results in a featureless expanse of ice. This flat ice may extend for many kilometers. The only surface features are snow drifts that form later in the winter.

Wind and/or water action early in the fall cause pancake ice (Figure 1.7) to form when nilas breaks into small pieces. As the pieces bump together their edges are rounded off and micro ridges are formed. Eventually they resemble rounded pancakes with a raised perimeter. These pancakes become frozen into a matrix of first-year ice and their

features are preserved for the remainder of the winter except for snow cover or subsequent deformation events.

Compressive forces cause nilas and thinner young ice to be deformed by finger rafting, which is the most common type of deformation (Figure 1.8). Finger rafting differs from simple rafting (one ice sheet riding over another) in that the ice fractures longitudinally forming fingers on both ice sheets that alternatively ride over or under the opposing finger. The effect is a doubling of the ice thickness in each finger. Micro ridges usually mark the borders of each individual finger, producing a distinctive square tooth pattern on the ice. Rafting events are also evident in thin ice when viewed from the air since the doubling of ice thickness produces a tonal change that is lighter than surrounding ice (Figure 1.8). Whereas finger rafting is limited to thinner ice, ordinary rafting may occur in first-year ice of any thickness. Rafting events during the fall usually leave a linear ridge with slight vertical development that is easily obscured by snow. When the ice sheet involved is more than 0.5 meters thick, a higher ridge forms on the surface. More than one rafting event may occur on a floe producing ice 3, 4, 5 or more thicknesses of the original ice. Most rafting events on the Beaufort Sea coast involve one or two rafting sheets, so that the ice thickness is, at most, tripled. Rafted ice thickness usually does not exceed 2.5 to 3 meters since the first-year ice nearshore becomes shorefast by December and does not move. When ice dynamics cease, no opportunities for rafting remain.

A discussion of the fall ice season is not complete without reference to the extreme ice motion events that have been recorded. There is evidence that the barrier islands have been at least partially covered by moving sea ice sheets up to one meter thick more than once during the last 20 years. Ice ride up onto beaches is fairly common with ice pileups nearly 12 meters high, reaching up to 20 meters inland. The barrier island events usually occur in the fall, while shoreline pileup events can occur during the fall and spring, when the first-year ice is free to move.

1.7 Ice Movement and Deformation

The movement and deformation of sea ice have special implications on oil spill cleanup. In the following paragraphs, ice movement and ice deformation processes are given special attention.

As a first approximation, sea ice moves in response to the wind along the Beaufort Sea coast. Currents are important to ice motion, but they are usually weak in nearshore areas. If strong currents are observed, as near a river mouth for example, then ice motion is determined by the current and can directly oppose the wind direction. Under normal circumstances the wind speed and direction can be used to estimate sea ice motion. The best estimate of ice motion is a drift speed of 2 to 3 percent of the wind speed and a drift direction up to 30 degrees to the right of the wind. Using this approximation, an east-northeast to northeasterly wind of 10 meters per second (20 kts) would move sea ice toward the west at 0.2 to 0.3 meters per second (0.4 to 0.6 kts). This approximation works well for open pack ice where some floe interactions occur. At the ice edge during break-up the drift speed may be closer to 3 to 5 percent of wind speed when no floe interactions impede ice drift. The contribution of currents can make ice drift appear to exceed 5 percent of the wind speed when the currents and the wind act together.

When there is less than 20 percent open water in pack ice, floe interactions can be expected to play a significant role in ice motion. Tremendous forces can be transmitted through the ice and the pack can move contrary to both the wind and currents in response to these forces. Internal ice forces can be generated by weather systems hundreds of kilometers from the coastline. It is not unusual for the ice over half the Beaufort Sea to move in response to a strong weather system located in the Arctic north of the Soviet Union.

In winter, ice movement is minimal in the shorefast ice sheets and in the stable portions of the shear zone. Measurements show that floating shorefast ice moves no more than a few meters. Generally larger amplitude motions occur farther offshore in deeper water.

Ice movement varies substantially in the shear zone. The stable part of the shear zone contains grounded ridges that are firmly anchored to the sea floor. In the floating part of the shear zone, ice is deformed by and moves in response to pressure from the polar pack ice. This floating ice may be moved by the polar pack or may even move with the polar pack.

During the shorefast ice season, the pack ice drifts at a slow rate. High ice concentrations in the pack impede movement and the normal wind field averages only about 5 meters per second (10 kts). This wind speed translates to a movement of 0.1 meters per second (0.2 kts) for the ice, assuming the 2 percent drift relationship. During dead calm periods, ice drift can be expected to be less than half this value, but sea ice continues to drift due to currents and internal forces that put pressure on the ice. Wind storms can produce pack ice motions of about 0.5 to 1 meter per second (1 to 2 kts) for time periods of less than one day.

During the break-up ice season, the shorefast ice becomes unstable and begins to move. At first, motions are limited to tens of feet as leads begin to open. As the leads widen and the pack ice no longer exerts pressure on the shorefast ice, large pieces of the sheet can break free and move about in the open water seaward of the shear zone. Ice movements may cover many miles under these conditions. The shear zone is weakening at the same time and floating pieces experience the same type of movement as the shorefast ice. Grounded pieces of ice resist movement until late in the break-up season, when they too become free and can drift for many miles before melting. In the pack ice, more motion becomes possible as the first-year ice between the multi-year floes begins to decay. Relatively light winds and infrequent storms usually cause the pack ice to move slowly but the pack readily responds to any change in the wind.

The summer season usually has open water in the areas once covered by the shorefast ice and the shear zone. Open water is also found north of where the shear zone had been as the pack ice retreats. Some multi-year floes or fragments of the shear zone are usually all that remain near the shore and these pieces of ice move with the wind and generally weak currents. Storms occur more frequently in summer than during break-up . Ice fragments may move many kilometers during these storms, and so does the southern edge of the pack ice, which is usually about 40 to 50 kilometers offshore.

The large number of storms that occur in the fall cause large movements of new and young ice forming near the shore. This ice cannot resist even moderate wind speeds and frequently moves many miles during storms. In fall, sea ice may also override barrier islands. During the most

intense storms these low-lying islands may be covered by ice 0.3 to 0.5 meters thick. Thicker ice may also pile up on the windward side of the island and cause extensive erosion. In addition, multi-year ice pieces may be surrounded by this moving first-year ice and carried along. Pieces of multi-year ice may also ride up on the barrier islands, although their deeper keels usually cause them to ground some distance away. These grounded multi-year pieces can then act as the nucleus for rubble piles that exceed 10 meters in height.

On the average new and young ice in the shallow waters of the Beaufort Sea probably move a number of kilometers during the fall ice season, although no public data exist to substantiate this estimate. New ice may not move at all during some years when storms are very weak or nonexistent; however, movement of tens of kilometers may occur in all water depths during stormy fall seasons. Although this movement has been observed, the frequency of occurrence has not been adequately determined. As a result, the average amount of ice movement in the fall is derived from widely separated observations and is not truly indicative of the motion of ice during any one season.

Deformed ice is a general term for ice that has been squeezed together and in places forced up and down, and for ice that has been subjected to diverging motion causing cracks or leads to form.

The World Meteorological Organization recognizes five deformation processes. These are fracturing, hummocking, ridging, rafting and weathering. Common usage has eliminated weathering from this list and it has been considered as a separate process. Fracturing refers to openings in a once solid or nearly solid ice sheet. These openings are called cracks, leads or polynyas depending upon their size and shape. In the shorefast ice, fracturing is common during fall season storms and during break-up (Figures 1.4 and 1.5). The shear zone experiences fracturing during break-up and the polar pack ice experiences fracturing, especially of the first-year ice, whenever ice motions cause divergence of the ice. Hummocking results from pressure in the ice and produces an area of broken ice pieces exhibiting a highly irregular surface. The Alaska Oil and Gas Association (AOGA) has adopted the more descriptive and widely used terms "rubble pile" or "rubble field" instead of hummocked ice. A rubble pile refers to a more vertical pile of sea ice, typically caused by a grounded feature, while a rubble field implies an area of broken ice, not necessarily caused by any grounded ice. Rubble piles and areas are formed in the fall and early winter in the shorefast ice and shear zone.

Ridging is the process in which pressure forces the ice into a line or wall of broken ice (Figure 1.10). The line may be sinuous, as in ridges formed by compression, or straight, as is common to ridges formed by shearing forces. In the shorefast ice, ridges form in the fall, but in the shear zone the process continues from the fall through the winter until break-up. Ridging can occur at any time in the pack ice.

Rafting occurs when one piece of ice overrides another (Figures 1.8 and 1.9). For ice up to about 12 centimeters thick, the floes thrust "fingers" alternately over and under the other to produce finger rafting. Thicker ice simply rafts an entire floe upon another. A pile of broken ice pieces is commonly pushed ahead of the rafting ice leaving a ridge-like feature on the ice surface. Rafting is very common throughout the Beaufort Sea in the fall season when the thin ice is easily deformed. As movement decreases in the shorefast ice, so

does rafting, but in an active shear zone rafting can continue until break-up. In the polar pack ice rafting is most common in first-year ice, especially during the fall. Multi-year ice floes are rarely subjected to rafting.

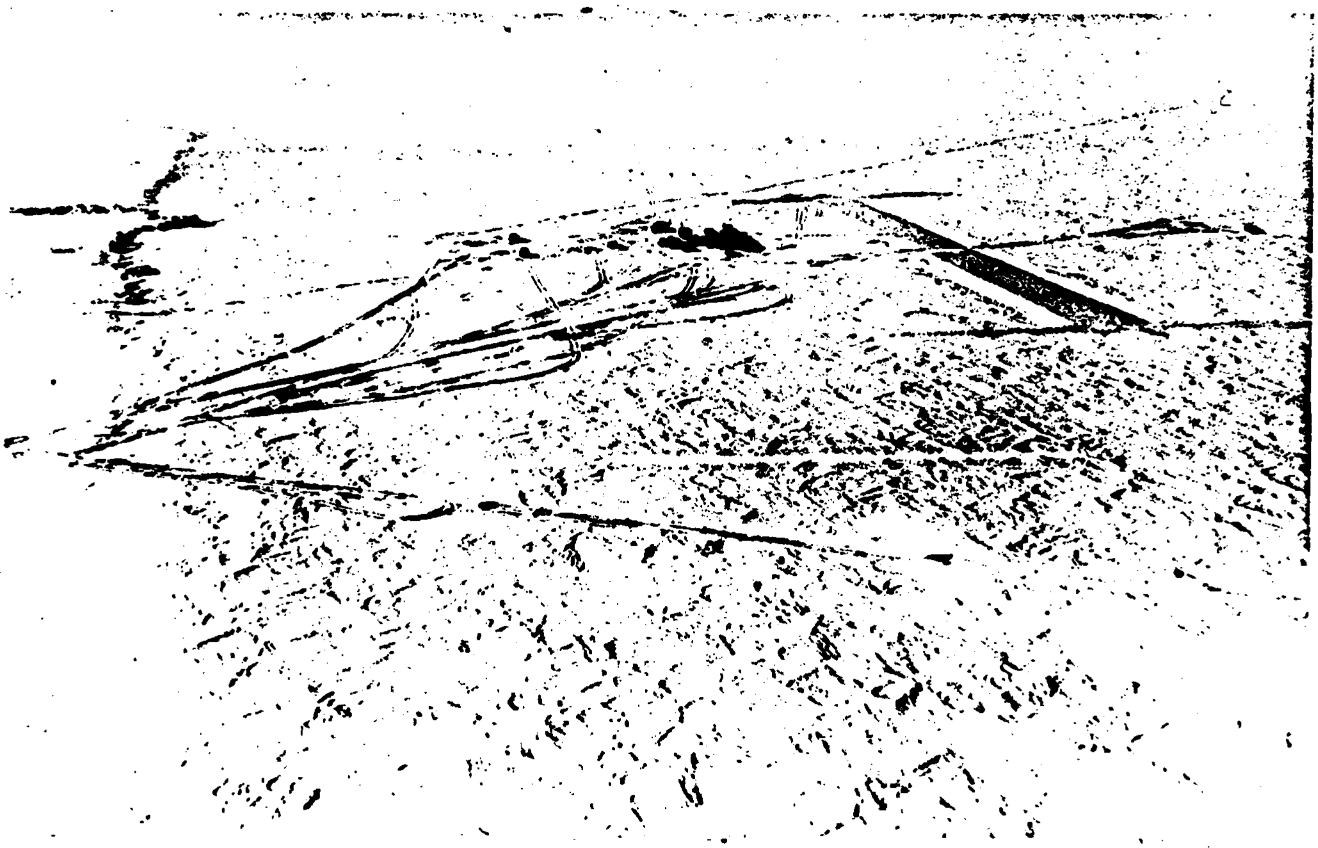

Figure 1.1 - Stable, shorefast first year ice.

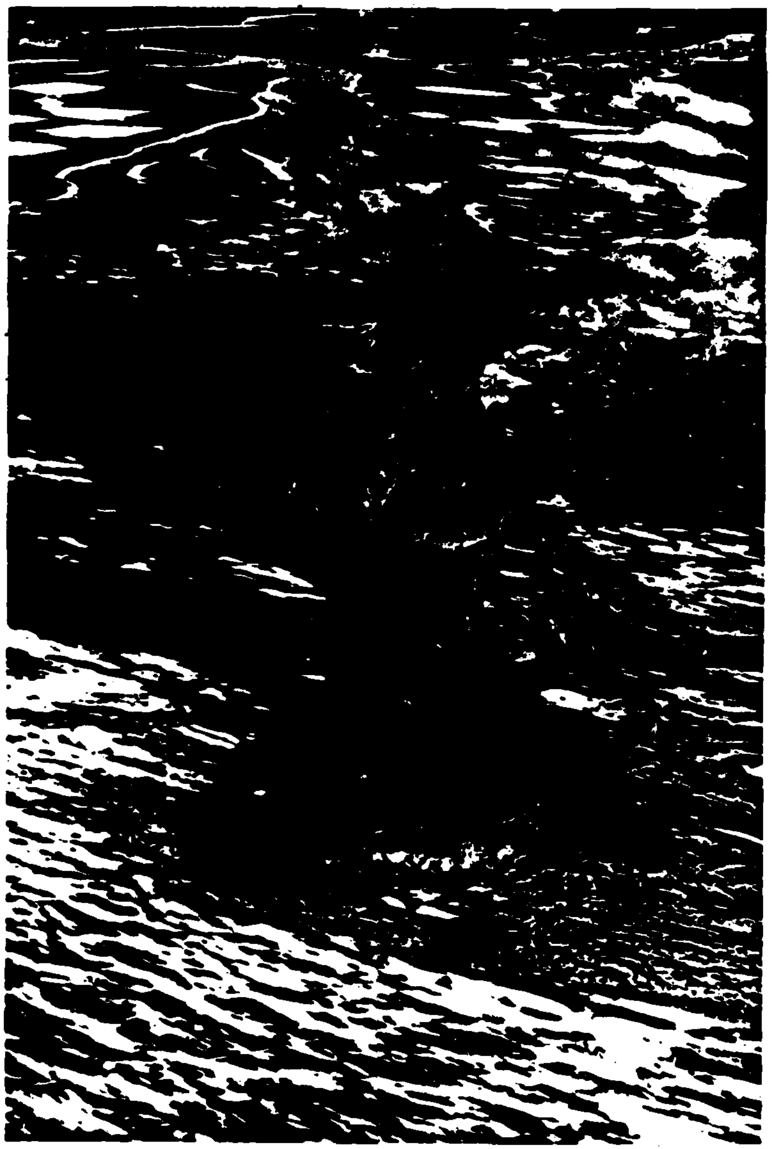

Figure 1.2 - Break-up at a river mouth. Decayed fast ice remains at the bottom of the photo but the river outflow has eliminated most of the ice near the river mouth. This occurs during early June.

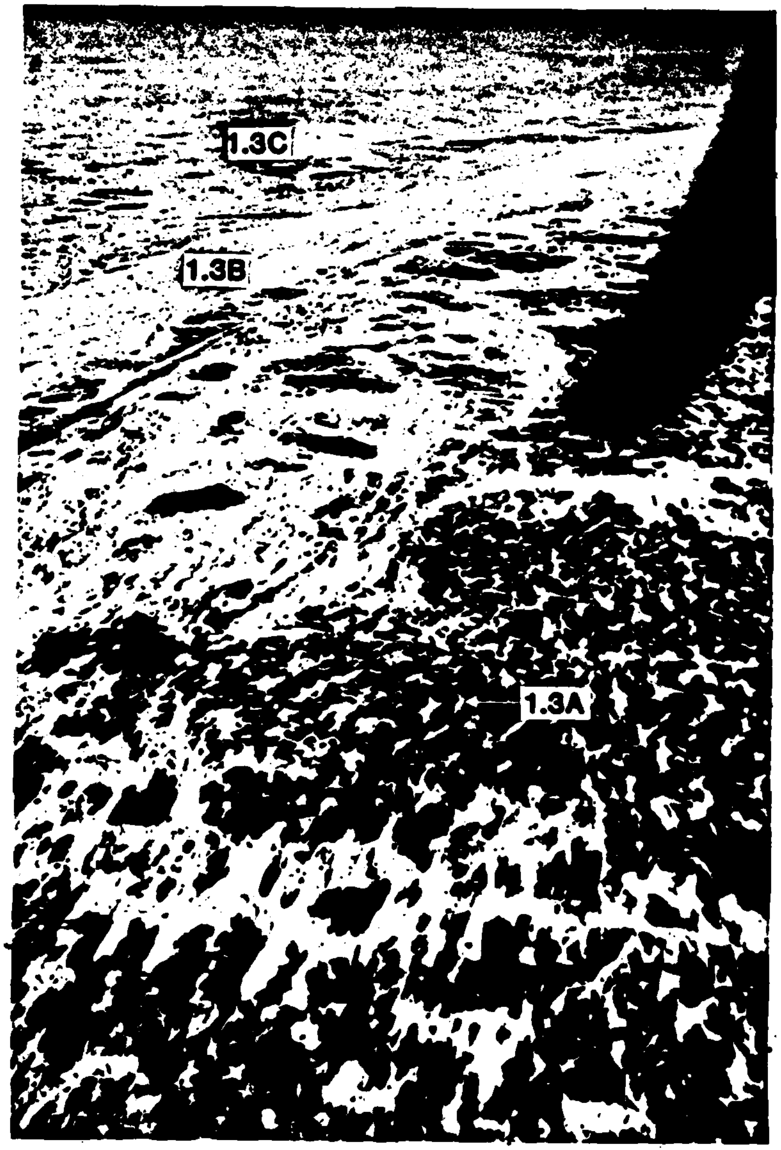

Figure 1.3 - Break-up photo. In the foreground the first year ice (1.3A) is covered by water except for the small ridges and highest snow drifts. Shear ridges (1.3B) run from left-center to the top-right and are not water covered due to their relief. In the more deformed first year (1.3C) ice, outside the shear ridges, water is being accumulated on flat ice.

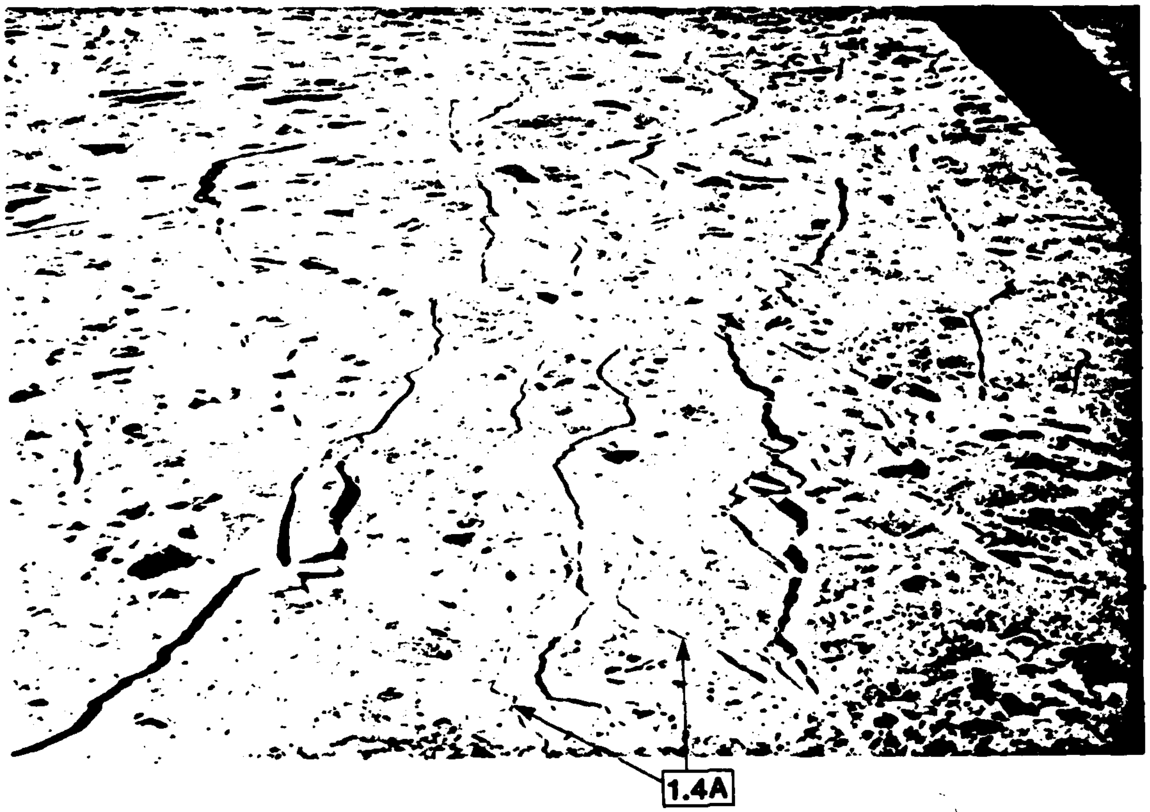

Figure 1.4 - Break-up of the first year ice. Cracks (1.4A) run through the ice indicating that it is no longer stable. Note water accumulation on ice surface.

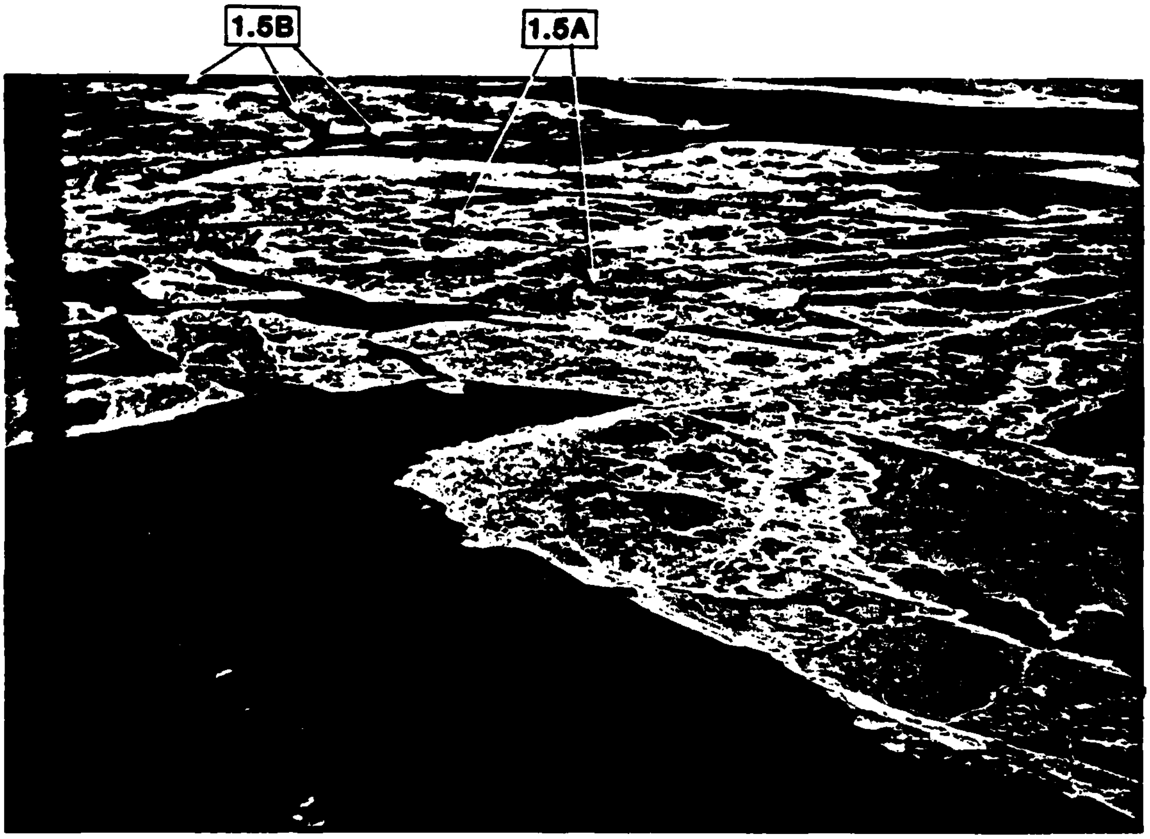

Figure 1.5 - Break-up nearly complete. Cracks (1.5A) and leads (1.5B) widen as the first year ice decays and disappears. The ice at the bottom-right of the photo is nearly ready to disintegrate.

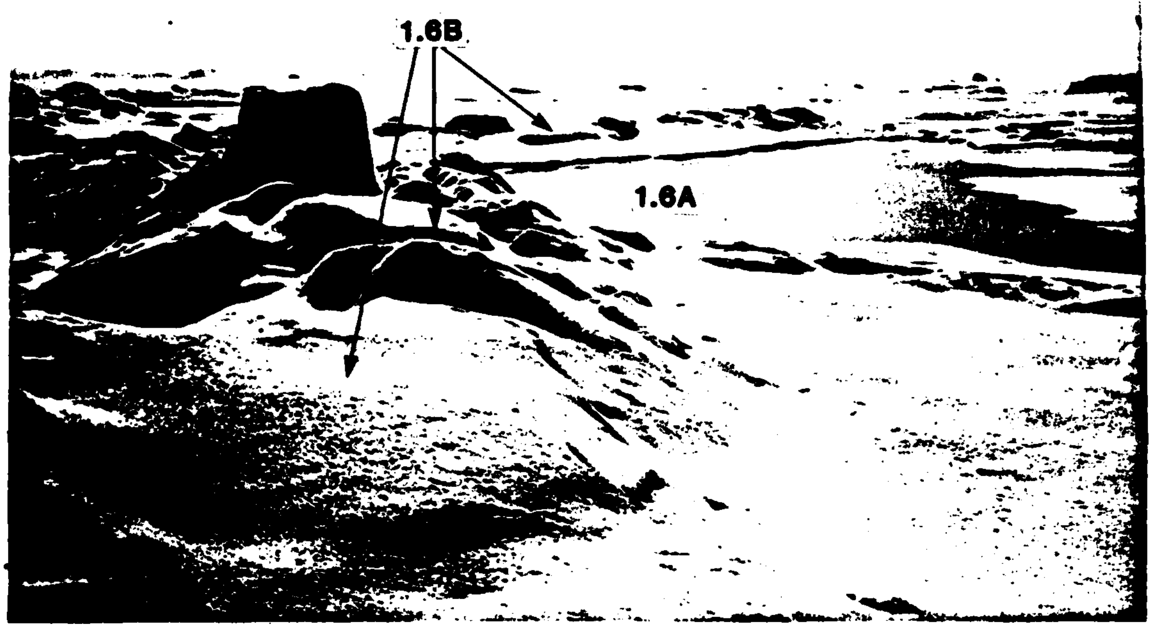

Figure 1.6 - Multi-year ice in summer. Note the melt-pool (1.6A) and rounded features (1.6B). The one prominent point along the ridge is rapidly melting and will vanish. Fog obscures the horizon, a typical summer condition.

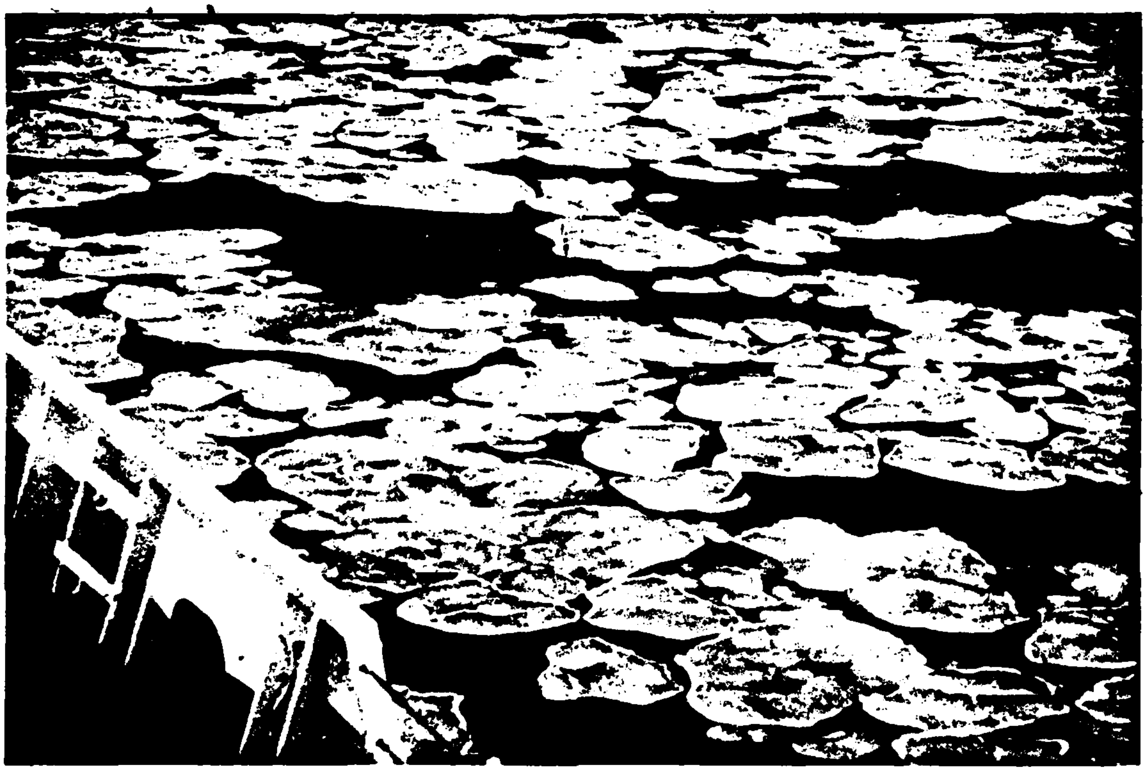

Figure 1.7 - Pancake ice. Note the round, thin floes and the tiny ridges around their circumference.

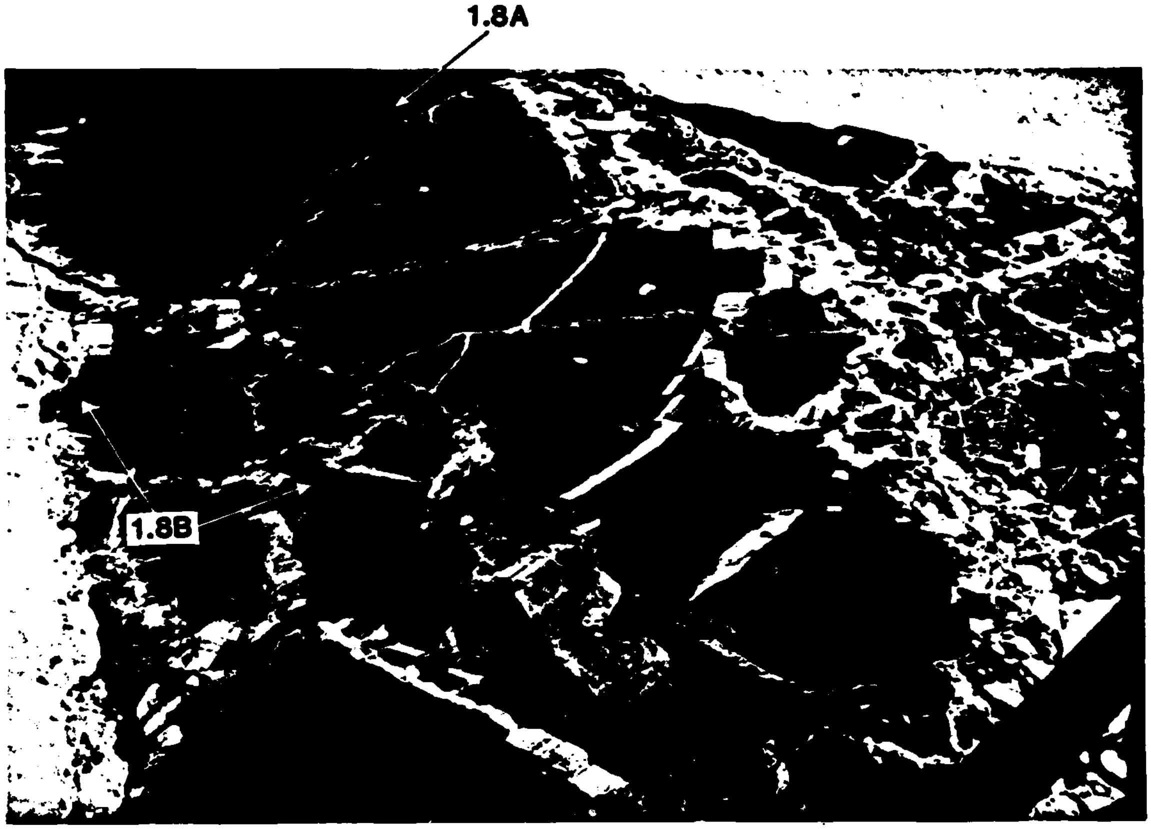

Figure 1.8 - Refrozen lead showing rafting. Nilas (1.8A)has broken into floes which have been rafted at their edges. Finger rafting (1.8B)is evident on much of photo, left-center especially.

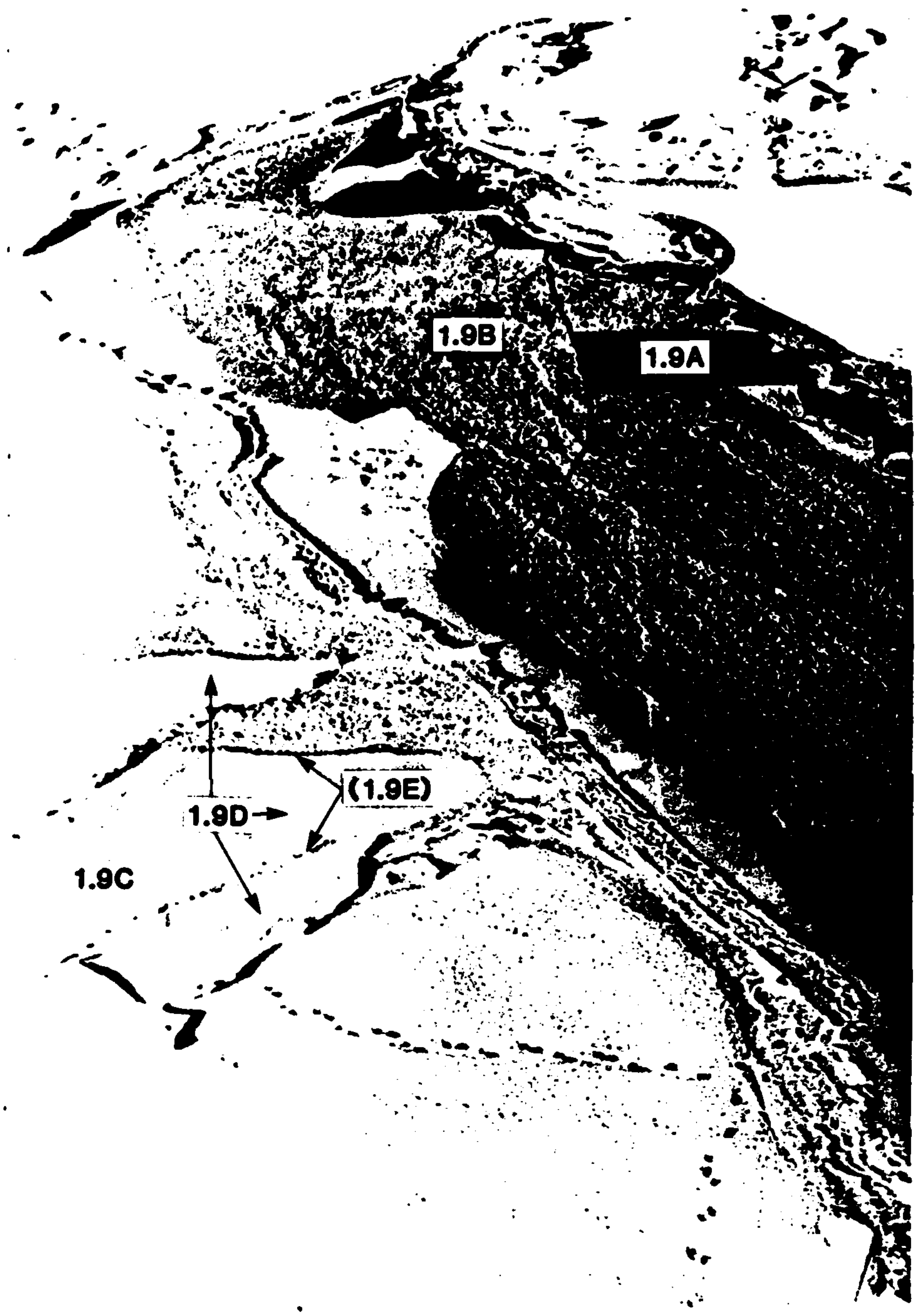

Figure 1.9 - Refrozen lead. Very dark areas are nilas, (1.9A) middle of lead is young ice (1.9B) and first year ice (1.9C) at bottom of photo. Note rafted pieces (1.9D) at bottom, left, and "micro" ridge (1.9E).

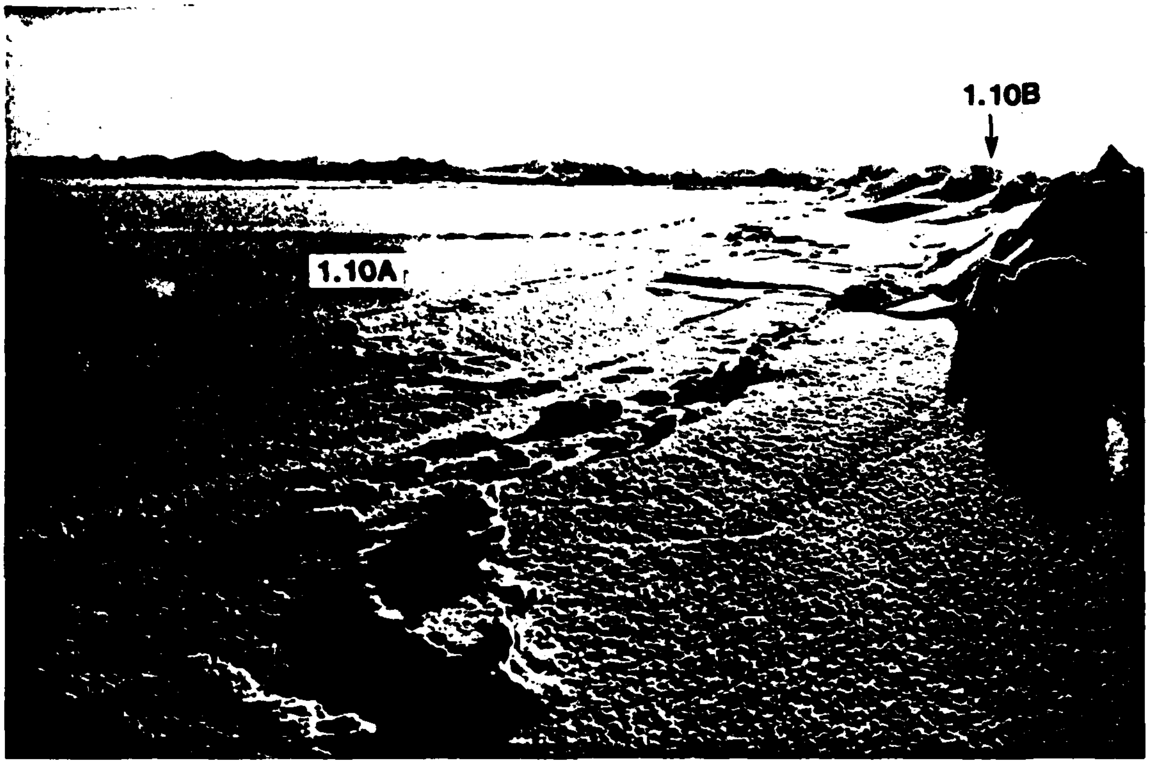

Figure 1.10 - Pressure ridging in young first year ice. The young ice (1.10A) in the center of the photo is being ridged (1.10B) on the right hand side. Note how large slabs are pushed up in this compression event (no shearing forces). The rough ice surface is caused by rapid ice formation and contains much salt--hence the name salt flowers.

ICE CONDITIONS REFERENCES

1. Aagaard, K., and contributors, Physical Oceanography and Meteorology, Environmental Assessment of the Alaskan Continental Shelf, Interim Synthesis: Beaufort/Chukchi, NOAA/OSCEAP, Boulder, Colorado, 1978.

2. Ackley, S. F., W. D. Hibler III, F. K. Kugzruk, A. Kovacs, and W. F. Weeks, Thickness and Roughness Variations of Arctic Multi-Year Sea Ice, AIDJEX Bulletin No. 25, University of Washington, Seattle, 1974.

3. Agerton, D. J., and J. R. Kreider, Correlation of Storms and Major Ice Movements in the Nearshore Alaskan Beaufort Sea, Proceedings Port and Ocean Engineering Under Arctic Conditions, Vol. 1, Trondheim, Norway, 1979.

4. Barry, R. G., Study of Climatic Effects on Fast Ice Extent and its Seasonal Decay Along the Beaufort-Chukchi Coasts, Environmental Assessment of the Alaskan Continental Shelf, Final Reports, NOAA/OCSEAP, Vol. 2, Physical Science Studies, Boulder, Colorado, 1979.

5. Bilello, M. A., Decay Patterns of Fast Sea Ice in Canada and Alaska, Sea Ice Processes and Models, Ed. R. S. Pritchard, University of Washington Press, Seattle, Washington, 1980.

6. Brower, W. A., H. F. Diaz, A. S. Prechtel, H. W. Searby, and J. L. Wise, Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, Vol. III, Chukchi-Beaufort Sea. Arctic Environmental Information and Data Center, U. of Alaska, Anchorage, Alaska, 1977.

7. Campbell, W. J., P. Gloerson, W. J. Webster, T. T. Wilheit, and R. O. Ramseier, Beaufort Sea Ice Zones as Delineated by Microwave Imagery, J. Geophys. Res., Vol. 81, No. 6, 1976.

8. Hunt, W. R., and G. M. Naske, A Baseline Study of Historic Ice Conditions in the Beaufort Sea, Chukchi Sea and Bering Strait, Environmental Assessment of the Alaskan Continental Shelf, Final Reports, NOAA/OCSEAP, Vol.1, Physical Science Series, Boulder, Colorado, 1979.

9. Kovacs, A., Grounded Ice in the Fast Ice Zone Along the Beaufort Sea Coast of Alaska. USA CRREL Report, 1976.

10. Kovacs, A, Sea Ice Thickness Profiling and Under Ice Oil Entrapment. Paper OTC 2949, 9th Annual Offshore Technology Conference, Houston, Texas, May 2-5, 1977.

11. Kovacs, A., and M. Mellor, Sea Ice Morphology and Ice as a Geologic Agent in the Southern Beaufort Sea, The Coast and Shelf of the Beaufort Sea, Eds. C. Reed and E. Slater, Arctic Institute of North America, Arlington, Virginia, 1974.

12. LaBelle, J. C., J. L. Wise, R. P. Voelker, R. H. Schulze and G. M. Wohl, Alaska Marine Ice Atlas, Arctic Environmental Information and Data Center, University of Alaska, 1983.

13. Markham, W. E., Ice Climatology in the Beaufort Sea, Beaufort Sea Project, Tech. Rpt. #26, 1975.

14. Mountain, D. G., L. K. Coachman, and K. Aagaard, On the Flow Through Barrow Canyon, J. Phys. Oceanography, Vol. 6, 1976.

15. Ramseier, R. O., M. R. Vant, L. D. Arsenault, L. Gray, R. B. Gray, and W. J. Chudobiak, Distribution of Sea Ice Thickness in the Beaufort Sea, Beaufort Sea Technical Report No. 30, Beaufort Sea Project, Dept. of the Environment, Victoria, B. C., 1975.

16. Reimnitz, E., L. J. Toimil, and P. Barnes, Arctic Continental Shelf Processes and Morphology Related to Sea Ice Zonation, Beaufort Sea, Alaska, AIDJEX Bulletin No. 36, University of Washington, Seattle, 1977.

17. Reimnitz E., L. J. Toimil, and P. W. Barnes, Stamukhi Zone Processes: Implications for Developing the Arctic Offshore, Proceedings 1977 Offshore Technology Conference, Vol. III, Houston, Texas, 1977.

18. Rogers, J. C., Meterological Factors Affecting Interannual Variability of Summertime Ice Extent in the Beaufort Sea. Monthly Weather Review, Vol. 101, 1978.

19. Shapiro, L. H. and Burns, J. J., Satellite Observations of Sea Ice Movement in the Bering Strait Region, Climate of the Arctic, (G. Weller and S. Bowling, Eds.) Proc. 24th Alaska Science Conference, Fairbanks, Alaska, Aug 15-17, 1973, 1975.

20. Stringer, W. J., Morphology of Beaufort, Chukchi and Bering Seas Nearshore Ice Conditions by Means of Satellite and Aerial Remote Sensing, Geophysical Institute, U. of Alaska, Fairbanks. 1978.

21. Thomas, D. R., and R. S. Pritchard, Beaufort and Chukchi Sea Ice Mortion; Part I. Pack Ice Trajectories, Environmental Assessment of the Alaska Continental Shelf, Annual Reports, NOAA/OCSEAP, Vol. VIII, Boulder, Colorado, 1979.

22. Thomas, D. R., Behavior of Oil Spills Under Sea Ice, Prudhoe Bay; Flow Research Report No. 175 in Environmental Assessment of the Alaskan Continental Shelf, Annual Reports, Vol. VI Transport, 1980.

23. Thorndike, A. S. and Chewing, J. Y., AIDJEX Measurements of Sea Ice Motion, 11 April 1975 to 14 May, 1976. AIDJEX Bull. 35, 1977.

24. Thorndike, A.S., and R. Colony, Large-scale Ice Motion in the Beaufort Sea during AIDJEX, April 1975-April 1976, Sea Ice Processes and Models, Ed. R. S. Pritchard, University of Washington Press, Seattle, Washington, 1980.

25. Thorndike, A. S., D. A. Rothrock, G. A. Maykut, and R. Colony, The Thickness Distribution of Sea Ice, J. Geophys. Res., Vol. 80, November, 1988.

26. Tucker, W. B., W. F. Weeks, A. Kovacs, and A. J. Gow, Nearshore Ice Motion at Prudhoe Bay, Alaska, Sea Ice Processes and Models, Ed. R. S. Pritchard, University of Washington Press, Seattle, Washington,, 1980.

27. Wadhams, P., Sea Ice Morphology in the Beaufort Sea, Beaufort Sea Technical Report No. 36, Beaufort Sea Project, Department of the Environment, Victoria, B. C., 1975.

28. Wadhams, P. and R. Horne, An Analysis of Ice Profiles Obtained by Submarine Sonar in the AIDJEX Area of the Beaufort Sea, Scott Polar Research Institute Technical Report, Cambridge, 1978.

29. Weeks, W., Sea Ice Conditions in the Arctic, AIDJEX Bulletin No. 34, University of Washington, Seattle, 1976.

30. Weeks, W. F., A. Kovacs, S. J. Mock, W. B. Tucker, W. D. Hibler, III, and A. J. Gow, Studies of the Movement of Coastal Sea Ice Near Prudhoe Bay, Alaska, U.S.A., J. Glaciology, Vol. 19, No. 81, 1977.

31. World Meterological Organization, WMO Sea-Ice Nomenclature: Terminology Codes and Illustrated Glossary, WMO Sea-Ice Nomenclature: Terminology Codes and Illustrated Glossary, WMO Publication No. 259. Technical Publication No. 145, Geneva, 1970.

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2.0 WEATHERING OF OIL

The information in this section was generated from a computer model developed by Dr. Donald Mackay of the University of Toronto. The U.S. Coast Guard Report CG-D-27-83, Development and Calibration of an Oil Spill Behavior Model (1), contains a listing of this program. We had to modify the program slightly to get the information we needed for the analysis. The paragraphs that follow describe the program and the modifications.

The computer modeling effort was divided into two phases. In phase 1 we computed spill evaporation rates and determined the physical properties of the oil as weathering progressed. In phase 2 we computed the radius of the slick as the oil spread.

Phase 1 began by establishing the initial program parameters. These include, 1) wind speed in knots, 2) duration of the spill in days, 3) temperature of the oil, and 4) equilibrium thickness of the slick in millimeters. We assumed that the spilled oil would quickly take on the temperature of the medium in which it is spilled. Oil spilled on water can be assumed to be close to the temperature of the water even though air temperature may be lower or higher. Following the same reasoning, we assumed oil spilled on ice to be close to the temperature of the ice even though this may be different from the air temperature.

Next, we calculated the physical properties of oil as it weathers using the equations and constants for each oil provided in the U.S. Coast Guard report. The model uses a set of equations for each physical property with appropriate constants for each oil type. The calculations were made for Prudhoe Bay crude and arctic diesel. It would be desirable to do a weathering analysis for other North Slope crudes, but their properties are not presently known, therefore only Prudhoe Bay crude is considered in the model. We also computed the physical properties for arctic diesel because this is virtually the only refined product used on the North Slope.

The constants needed in the model are available for Prudhoe Bay crude but not for arctic diesel. In order to run the model and develop a comparable set of data, constants for #2 heating fuel were substituted for arctic diesel. This substitution was justified because the constants represent slopes of curves based on laboratory tests. Substituting the constants for a similar product only changes the origin of the curves slightly - the properties equations work the same way. Arctic diesel can be expected to evaporate somewhat faster than #2 fuel oil, but most properties of these two products can be expected to be much the same. Table 2.1 shows the baseline properties used in the model for arctic diesel and Prudhoe Bay crude.

After the physical properties were determined, the amount of oil evaporated was calculated in hourly increments for the duration of the spill. At the end of each hour, the thickness was decreased to account for the loss due to evaporation. New oil properties were determined based on the amount of oil that evaporated. The effects of dispersion, emulsification, and spreading were not considered in Phase 1.

Phase 2 focused on the spreading process. The equations developed by Don Mackay are based on two slicks forming after a spill occurs (1). The first slick is a heavy accumulation of oil at the source of the spill This thick slick bleeds out into a fine sheen that moves out rapidly

TABLE 2.1

OIL PROPERTIES AT 25°C

Property	Prudhoe Bay Crude	Arctic Diesel
Density	0.895 g/cc	0.804 g/cc
Viscosity	35.0 cps*	0.418 cps*
Solubility	29.2 g/m^3	3.0 g/m^3**
Pour point	-9.4°C	-51.0°C

* CPS - centipoise

** Value for #2 fuel oil; solubility for arctic diesel not available.

to cover a large area. The thin slick covers an area approximately eight times the area of the thick slick. For this analysis, the thin slick was set at 5 microns. The thickness of the thick slick for Prudhoe Bay crude was 4 cm and for arctic diesel was 2 cm. The thick, central part of the spill is caused by oil piling up at the source of the spill.

After the slick thickness is specified, the model proceeds essentially in the same general manner as in Phase 1. For example, the initial physical properties are calculated. Then the fraction of oil evaporated from the thick slick is calculated in hourly increments. The amount of oil emulsified is also determined incrementally.

The next step is to calculate the change in volume and area of both slicks based on the evaporation and emulsification processes. The equations in the model are based on the principle that the thick slick feeds the thin slick until both slicks have the same thickness and the process stops. The thick slick area decreases by the same amount as the thin slick increases. For each time step a new area, volume, and thickness are calculated for the thick slick. The thin slick thickness is assumed to remain constant. In Phase 2 the effects of dispersion are not considered.

These mathematical models represent simplified conditions. Environmental conditions such as waves, currents, spills on or under ice , and their effects on the evaporation and the spreading process are not taken into account. These models generate information based on the assumption that a spill occurred on open water without waves.

2.1 Evaporation

The evaporation characteristics of spilled products are described in terms of the variables that affect evaporation, that is:

- Slick thickness

- o Wind velocity
- o Temperature
- o Oil/ice/snow configuration

Differences in evaporation caused by slick thickness, wind velocity and temperature are determined from the weathering model. The oil/ice/snow configuration refers to spill situations in which oil is on ice, snow, pressure ridges, ice rubble and so forth. Differences in evaporation rates caused by the oil being mixed with ice or snow are not computed in the weathering model; however, these differences have been reported in some field test results and in actual spill situations. These differences are therefore reported separately at the end of this section.

2.1.1 <u>Slick Thickness</u>

<u>Prudhoe Bay Crude.</u> We ran the weathering model to show evaporation rate for slick thicknesses of 1, 5, 10, and 20 mm. Crude spilled on cold water (temperature range of -2°C to 0°C) is expected to reach an equilibrium thickness of 5 mm, or at least in the range of 5 to 10 mm (2). Other thicknesses of crude are also possible when the spill occurs in an ice environment. For example, oil deposited on ice could be quite thick, therefore we used the evaporation rate for a relatively thick slick of 20 mm. Oil on ice could also be fairly thin, probably as a result of the oil being deposited in the form of a spray, so we also included a 1 mm slick.

Figures 2.1.1 through 2.1.4 show the computed evaporation rate for four thicknesses of Prudhoe Bay crude oil. All of these curves begin with 100% of the oil remaining, but the steep slope at time zero emphasizes the fact that the most significant evaporation occurs in the first few hours that the oil is exposed. After the second or third day of exposure there is some additional loss by evaporation, but not very much. These curves show that as the slick thickness increases, the percent oil remaining also increases. This simply means that for thicker accumulations of oil, a large volume of oil has less surface area available for evaporation.

<u>Arctic Diesel</u>. Figures 2.1.5 through 2.1.9 show the evaporation rate for increasing thicknesses of arctic diesel. Figure 2.1.5 shows evaporation for a slick of 0.005 mm or 5 microns. If the diesel spill is free to move in all directions it is likely to go to a sheen; therefore, 5 microns may not be a terminal thickness, but it is likely to be the last thickness at which evaporation (and probably mechanical recovery) would be considered. A relatively high percentage of the arctic diesel is expected to evaporate.

In many seasons in the Arctic, a diesel spill may be confined by ice, so the curves also show the evaporation rate for slick thicknesses up to 20 mm.

2.1.2 <u>Wind Velocity</u>

Evaporation curves are plotted for a wind evelope of 5 and 20 knots. We selected this range because winds in the southern Beaufort Sea are generally not less than 5 knots and rarely greater than 20 knots. The average wind for most areas is about 13 knots, which is near the center of the envelope shown.

The curves for both Prudhoe Bay crude and arctic diesel show that wind velocity is important to evaporation, but probably not as significant as one would expect. On most of the curves, an increase in wind speed from 5 to 20 knots results in an increase in evaporation of about 3%. For the thicker slicks of arctic diesel, increased wind

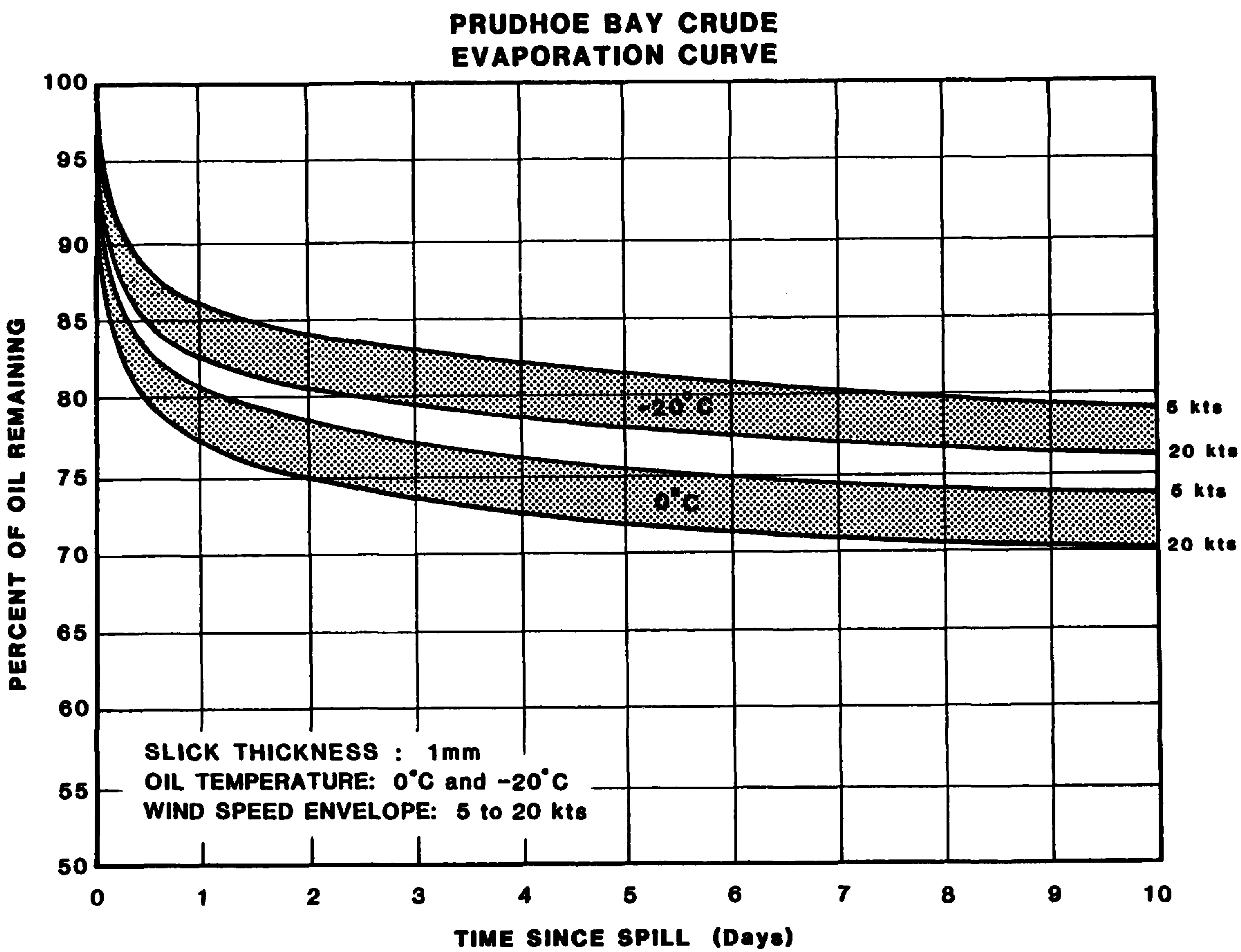


FIGURE 2.1.1 EVAPORATION OF PRUDHOE BAY CRUDE - Slick Thickness of 1 mm

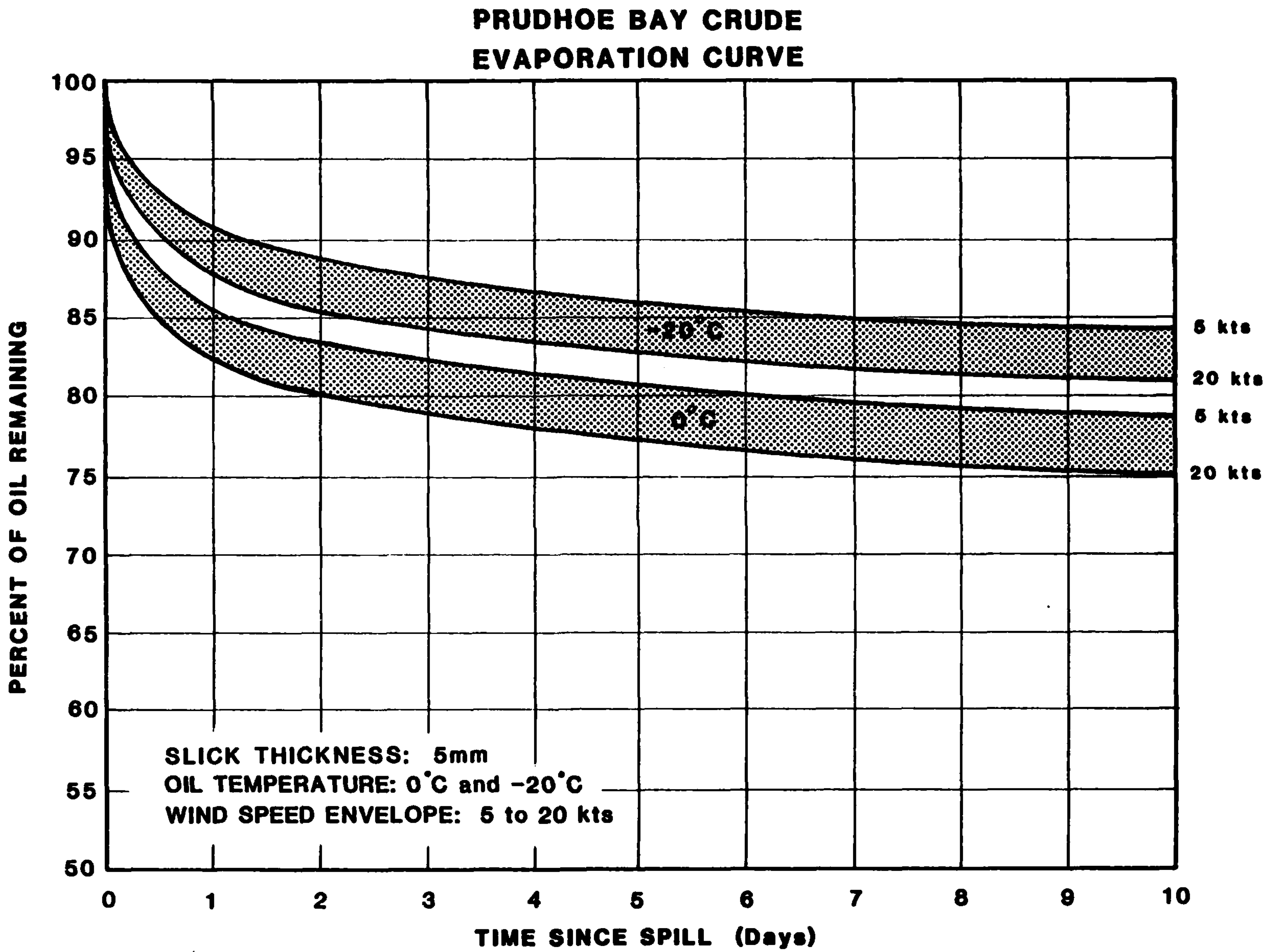


FIGURE 2.1.2 EVAPORATION OF PRUDHOE BAY CRUDE - Slick Thickness of 5 mm

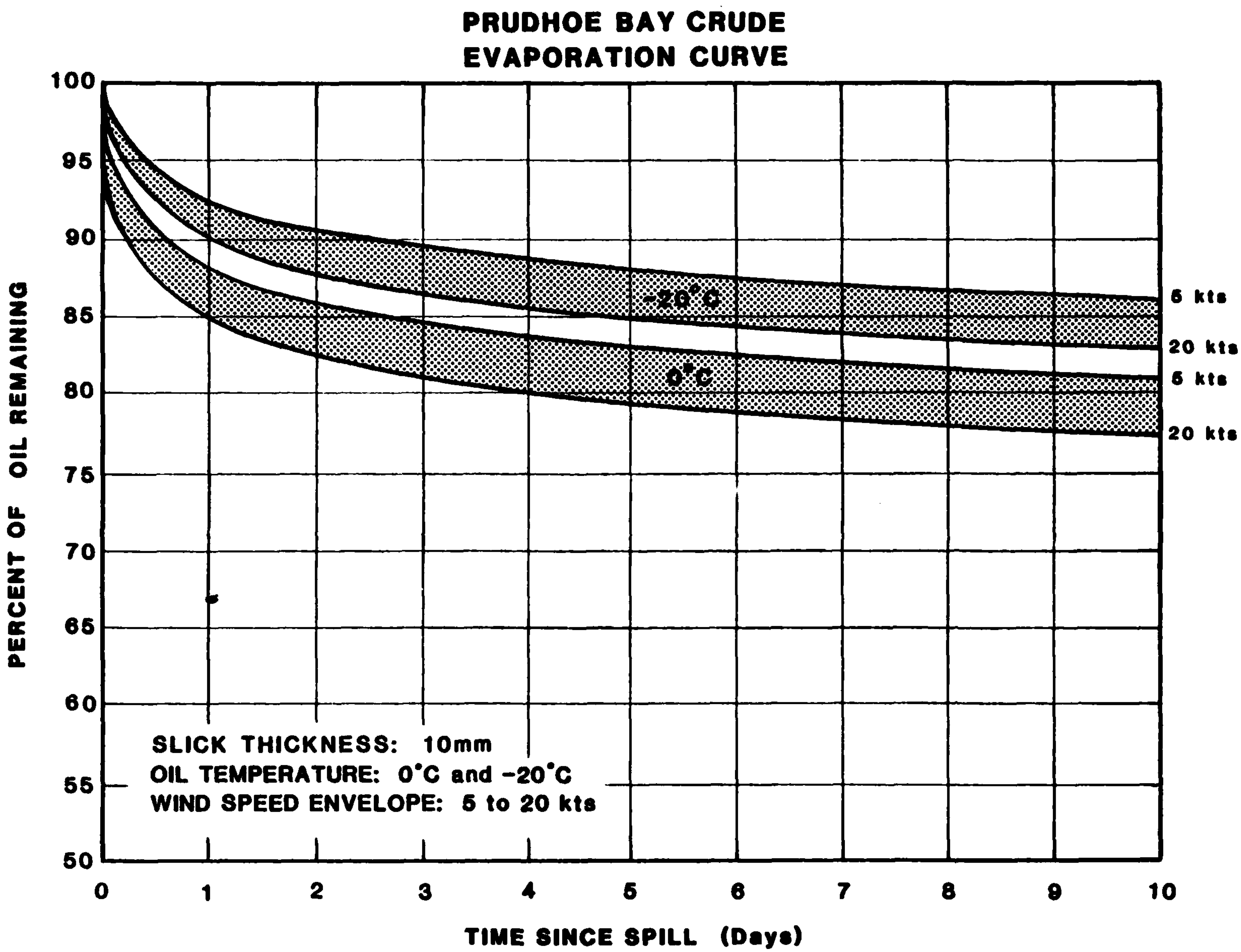


FIGURE 2.1.3 EVAPORATION OF PRUDHOE BAY CRUDE - Slick Thickness of 10 mm

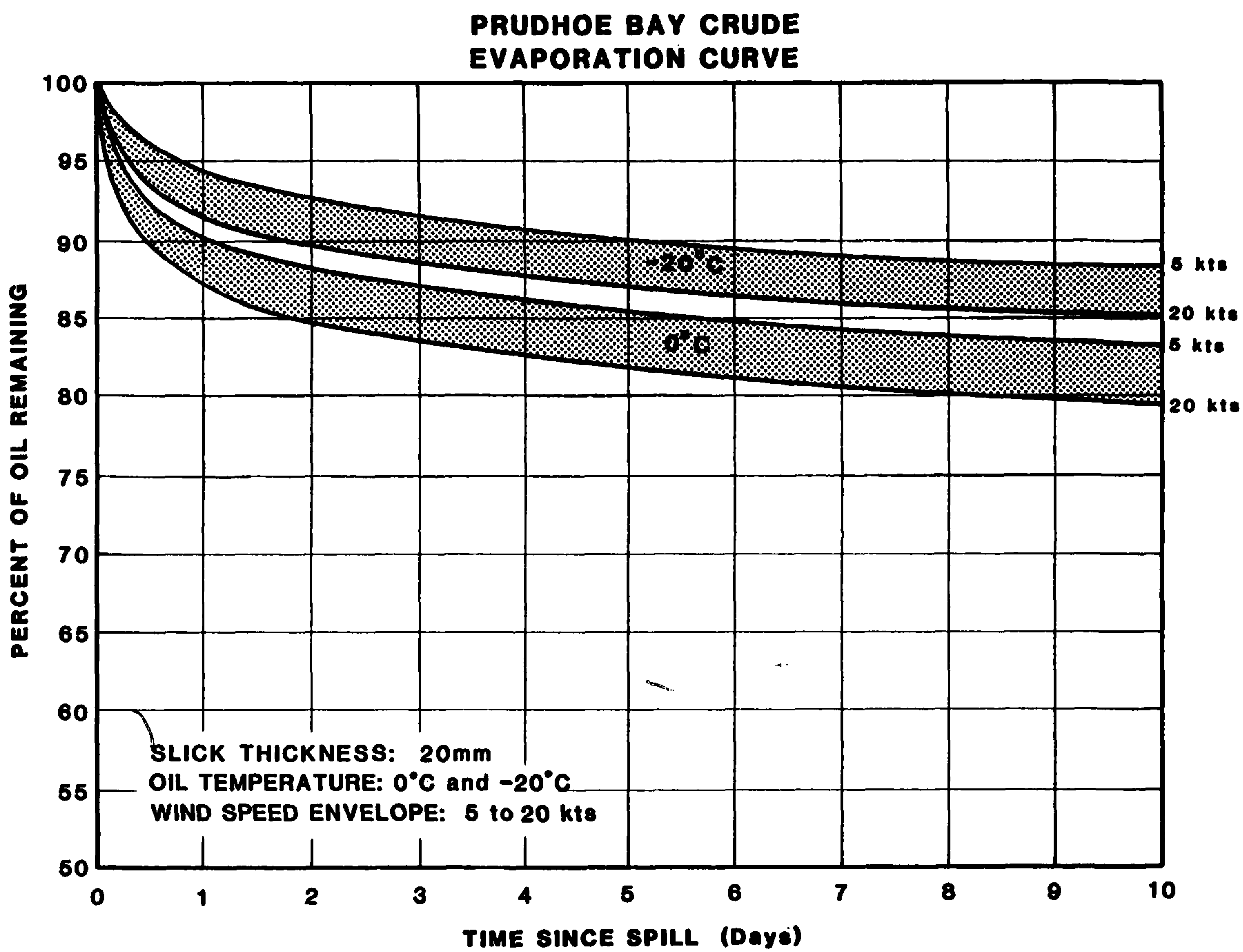


FIGURE 2.1.4 EVAPORATION OF PRUDHOE BAY CRUDE - Slick Thickness of 20 mm

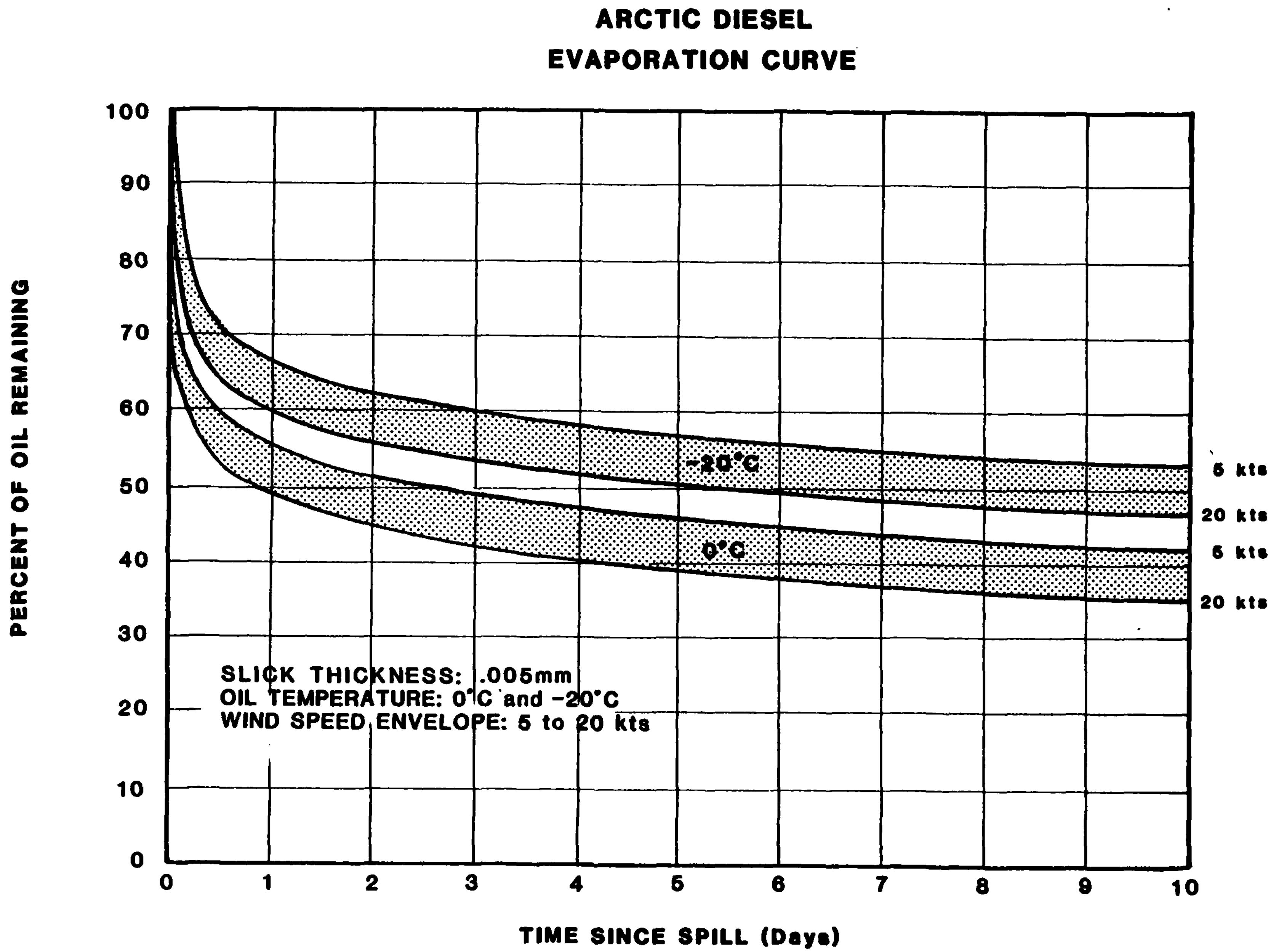


FIGURE 2.1.5 EVAPORATION OF ARCTIC DIESEL - Slick Thickness of 0.005 mm

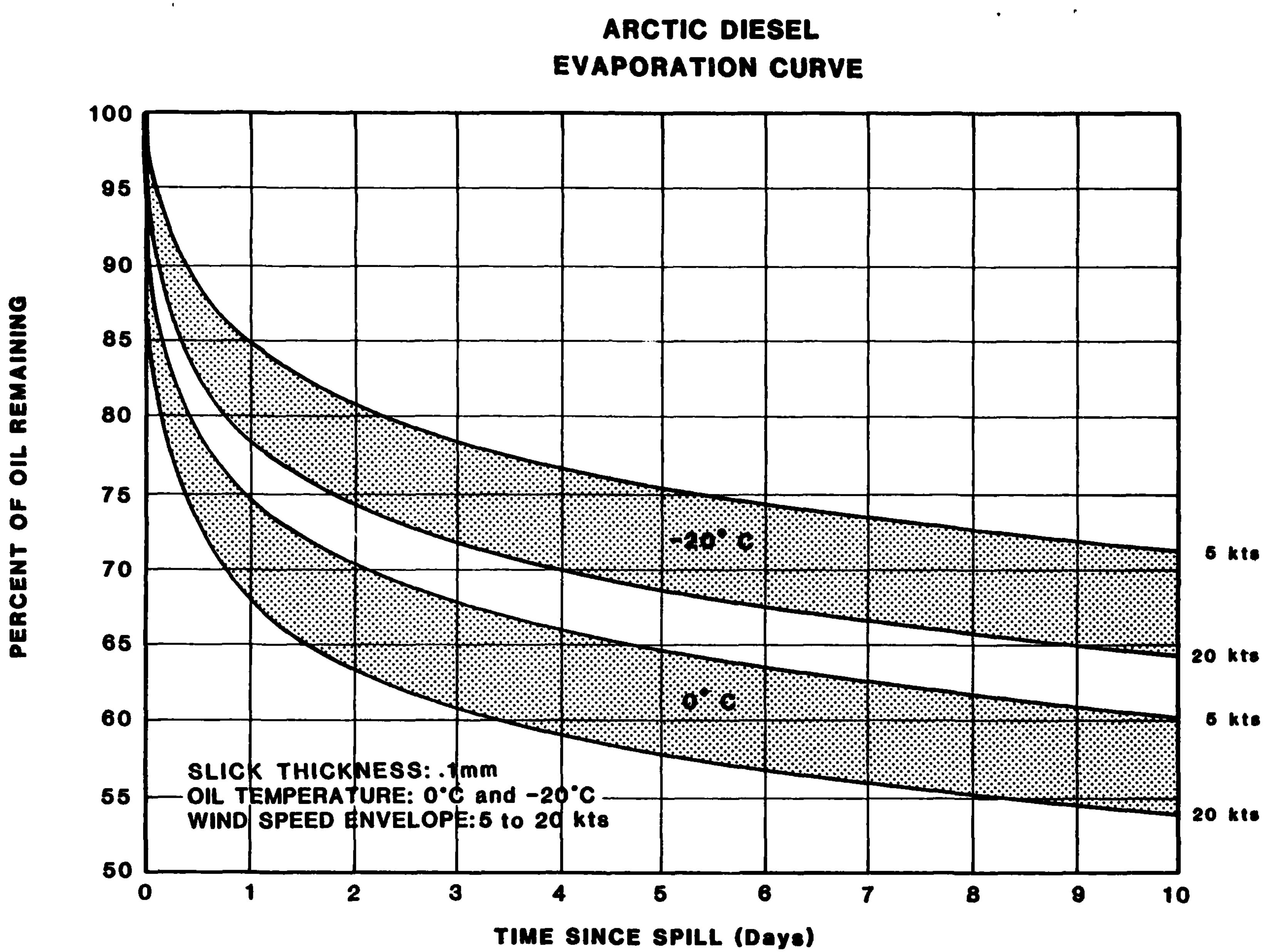


FIGURE 2.1.6 EVAPORATION OF ARCTIC DIESEL - Slick Thickness of 0.1 mm

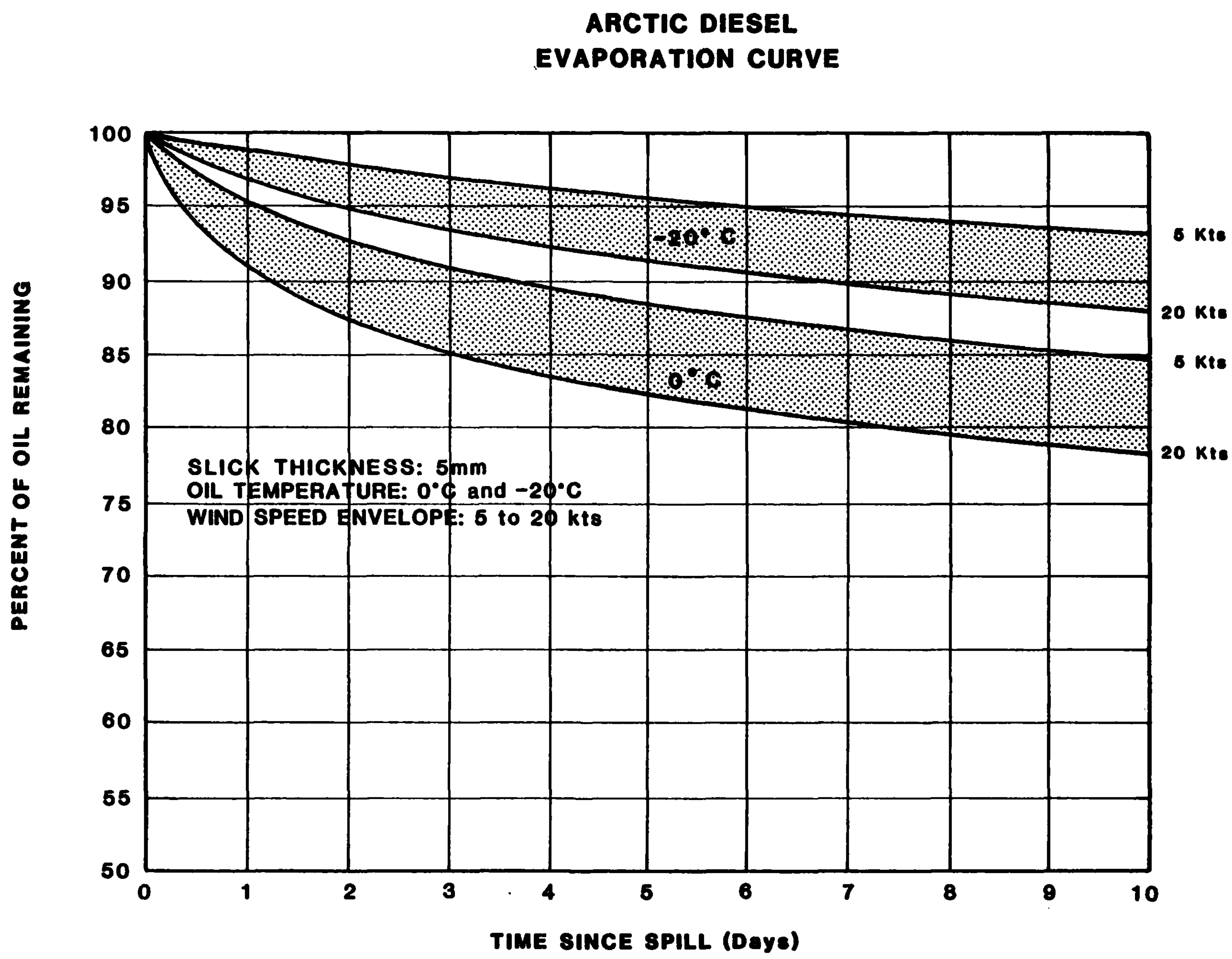


FIGURE 2.1.7 EVAPORATION OF ARCTIC DIESEL - Slick Thickness of 5 mm

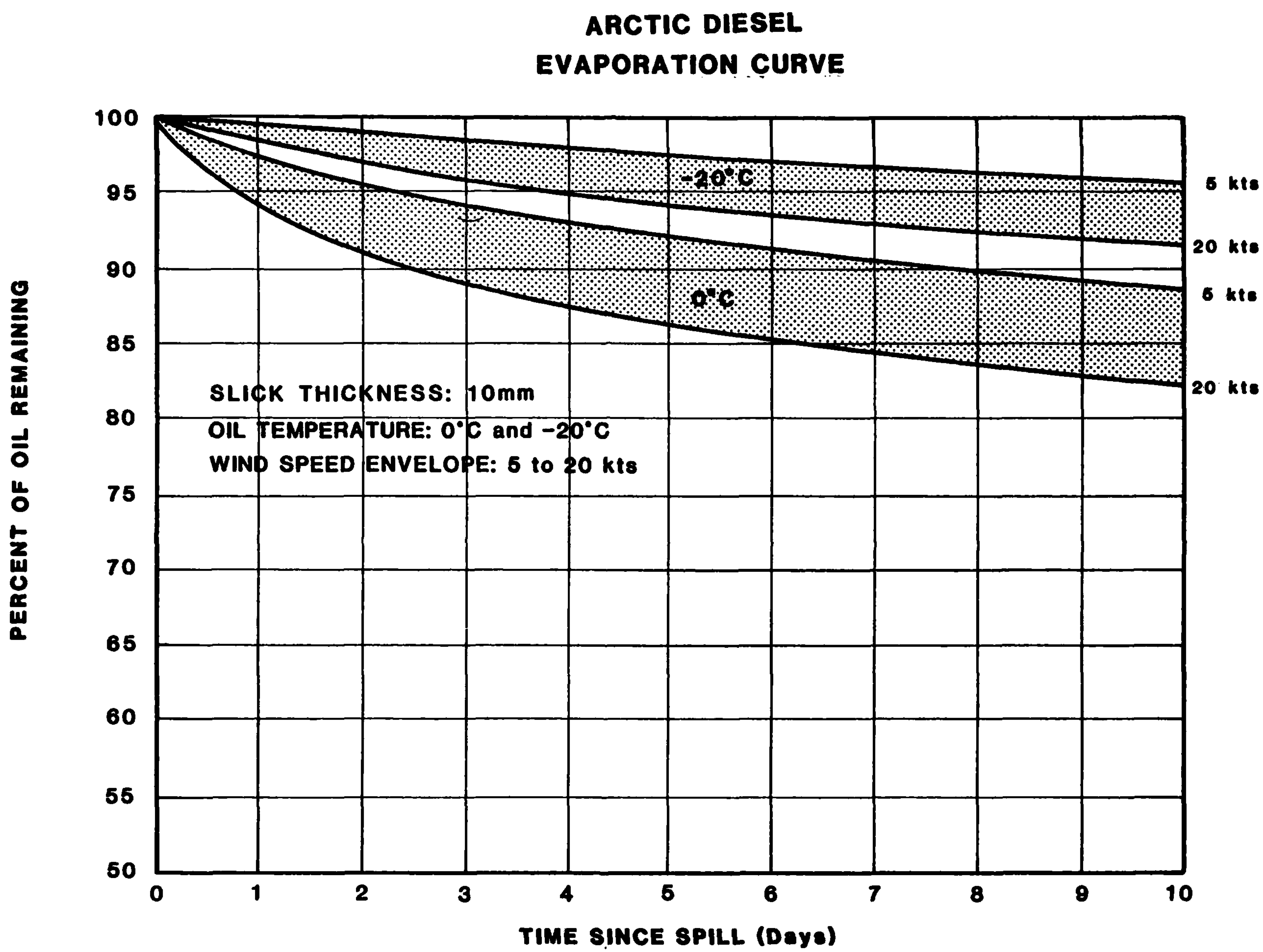


FIGURE 2.1.8 EVAPORATION OF ARCTIC DIESEL - Slick Thickness of 10 mm

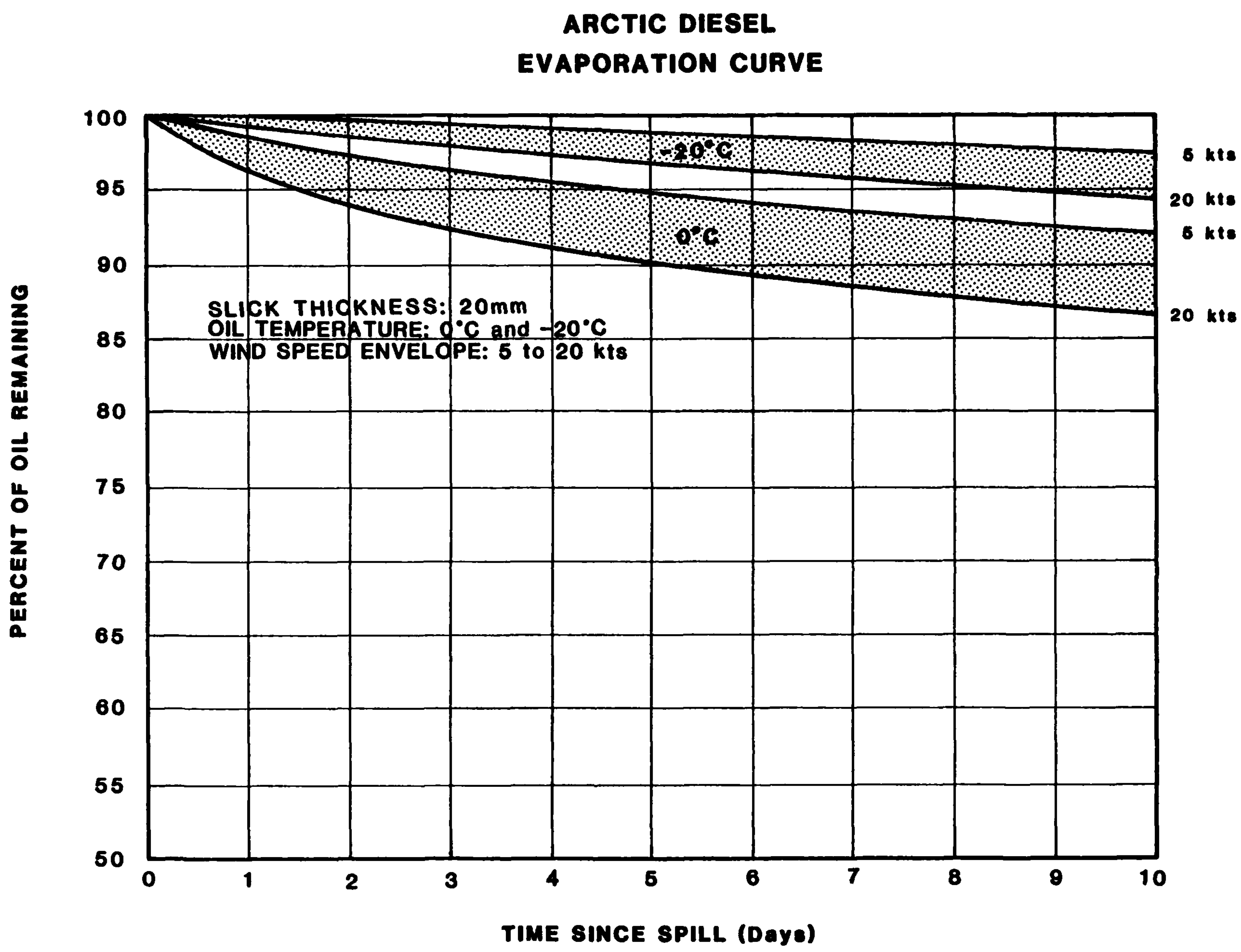


FIGURE 2.1.9 EVAPORATION OF ARCTIC DIESEL - Slick Thickness of 20 mm

speed causes about 7% more evaporation.

2.1.3 Temperature

The evaporation curves also show how temperature affects evaporation. The general relationship is that as temperature decreases, evaporation is reduced. For Prudhoe Bay crude, there is about 3% less evaporation for each 10°C drop in temperature. For arctic diesel, there is about 6% less evaporation for each 10°C drop in temperature, but this relationship is not quite as regular.

Remember that the important temperature is the temperature of the oil. Oil spilled on water can be expected to quickly take on the temperature of the water. In the southern Beaufort Sea this is generally in the range of -2°C to 0°C. Unusually high air temperatures in late summer can cause the water to be slightly higher than 0°C, but not much. If the spill is on ice, the oil will take the temperature of the ice. In winter the ice could be as cold as -20°C, but it may not be as cold as the air. There are no records of average ice temperatures. Ice temperature has to be measured at the spill site.

2.1.4 Oil in Ice and Snow

Evaporation can be expected to be greatly reduced when oil is mixed with ice or snow. If the oil is incorporated in the ice, evaporation is virtually stopped. In the Canadian Beaufort Sea test of 1975, NORCOR estimated that light oil in ice evaporated at a rate of 2 to 5% per month and heavy oil 1.5% or less per month (3). In the same tests light oil on the surface of ice evaporated at a rate of 7 to 28% per month and heavy oil at a rate of 1.5 to 19% per month.

Reports of actual spills show how evaporation rate changes for spills in an ice environment. In the spill of diesel on ice at Deception Bay in 1973, Ramseier noted that the oil was quickly absorbed by porous ice and the evaporation rate was only about 25% of the rate from the free surface (4). In a spill of #2 fuel oil on ice in Buzzard's Bay Massachusetts, observers reported that after 12 days the oil under the ice lost 6% of its volume, oil mixed with snow lost 12% of its volume, oil pooled on ice lost 13%, oil spread thinly over ice lost 30%, and oil absorbed into the ice projecting into the air lost 47% of its volume (5). These results show that a wide variation in weathering is possible depending on how the oil spreads over the ice and the area that is exposed to the air.

The evaporation of oil in various kinds of ice conditions has not been thoroughly investigated to date. Evaporation rates of oil mixed with ice are likely to be highly variable depending of the type of oil, how it is mixed with the ice, environmental conditions, and the amount of exposure. An accurate method of predicting these evaporation rates is not presently available.

2.2 Viscosity

Viscosity is very important in determining how a spill may spread and how it can be handled for recovery. Basically, crudes become highly viscous when they are weathered at low temperatures. This means that they will not spread very much and for recovery they would be handled almost as a solid (6).

Figures 2.2.1 through 2.2.4 show the changes in viscosity for Prudhoe Bay crude weathering in arctic conditions.

Figure 2.2.1 shows that viscosity increases rapidly in the first few

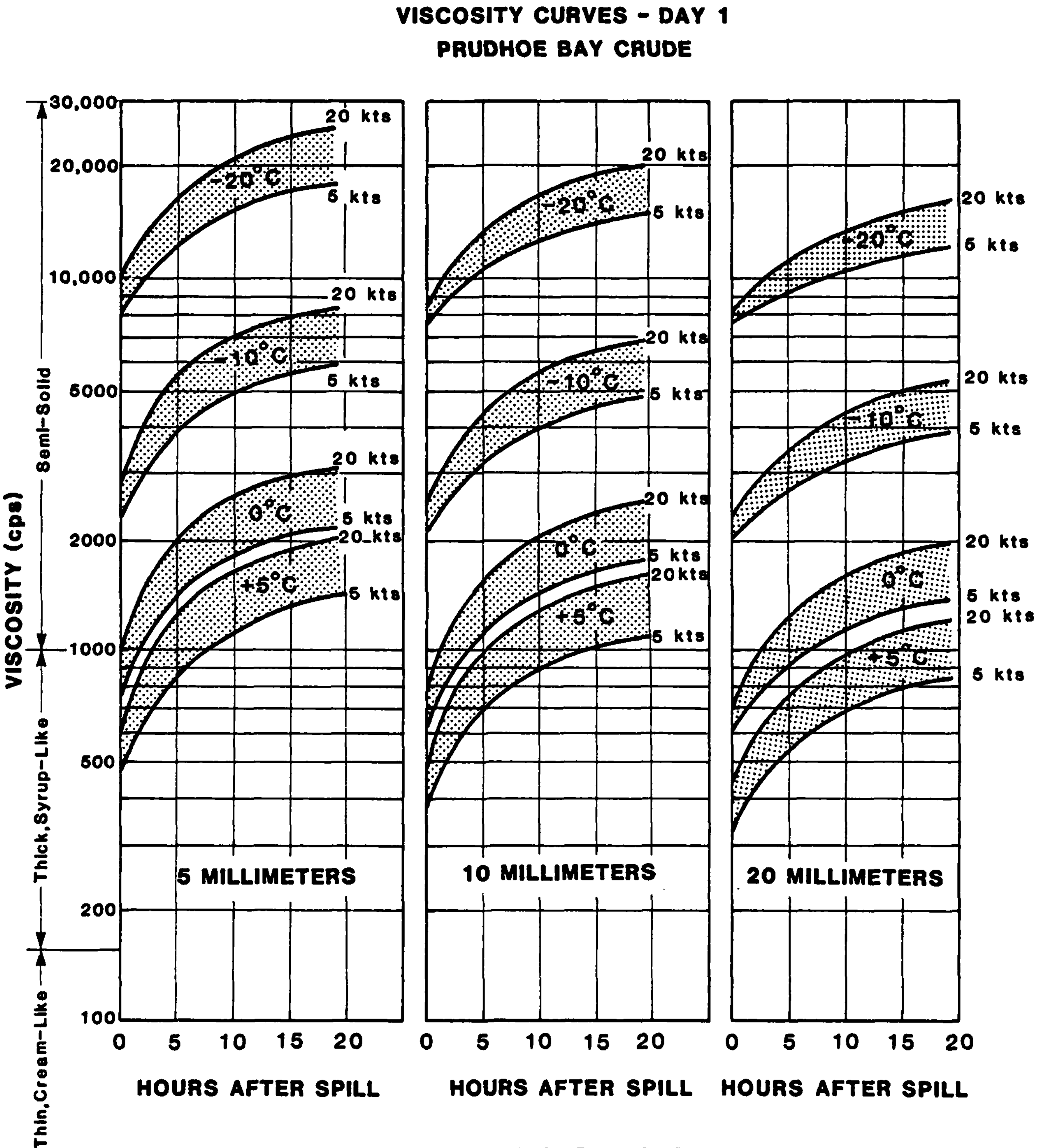


FIGURE 2.2.1 VISCOSITY OF PRUDHOE BAY CRUDE - First day of exposure

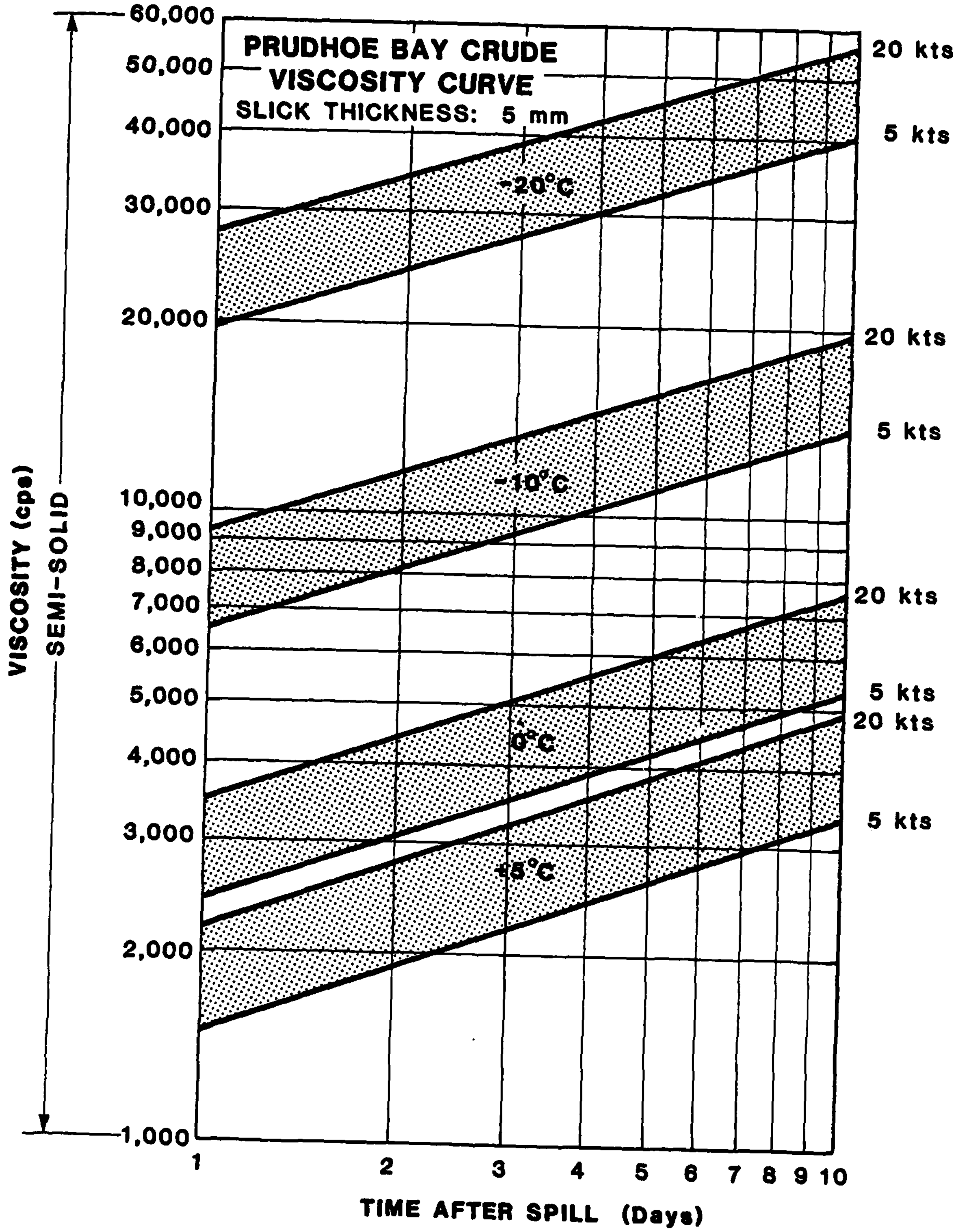


FIGURE 2.2.2 VISCOSITY OF PRUDHOE BAY CRUDE - 5 mm slick, days 1 through 10

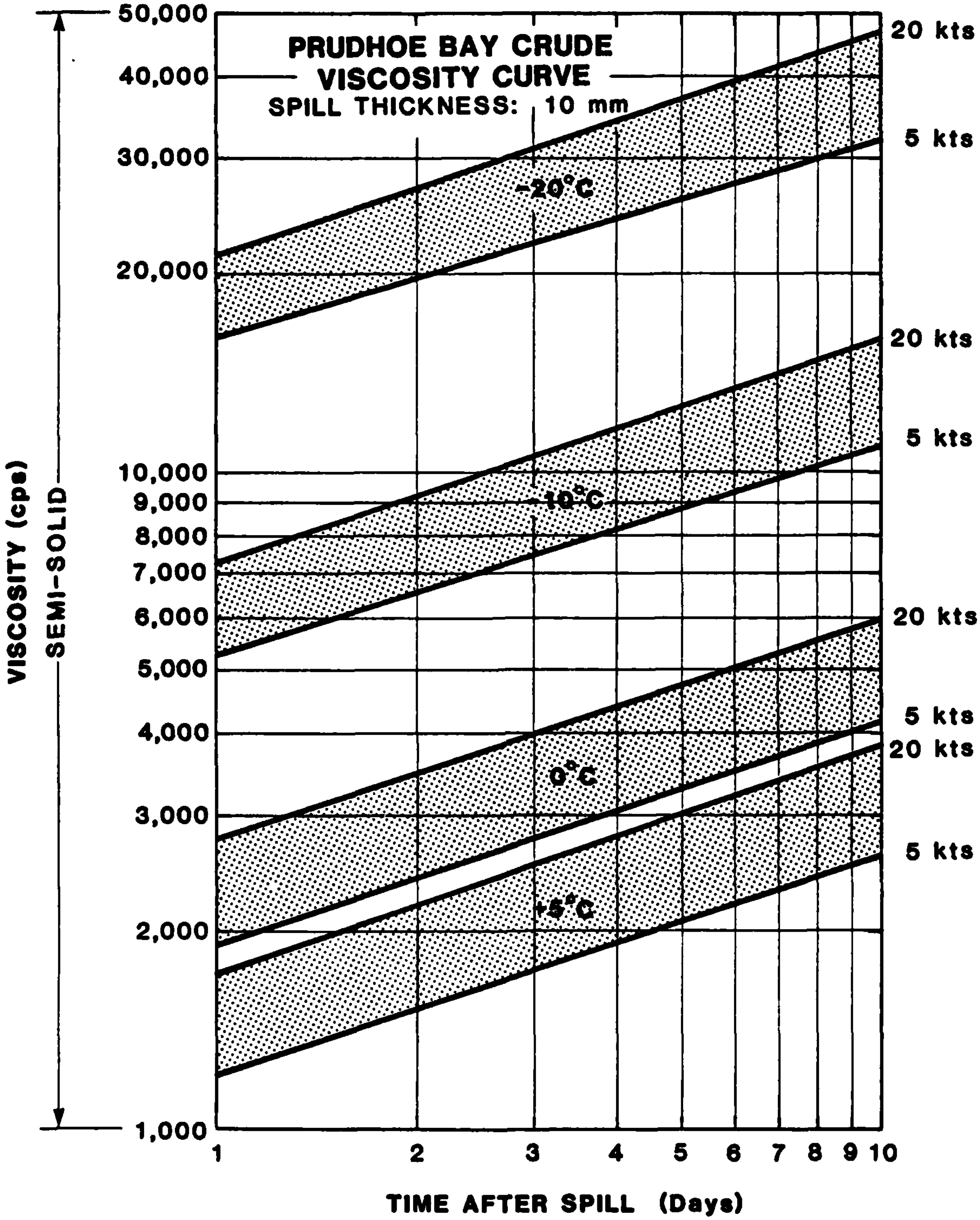


FIGURE 2.2.3 VISCOSITY OF PRUDHOE BAY CRUDE - 10 mm slick, days 1 through 10

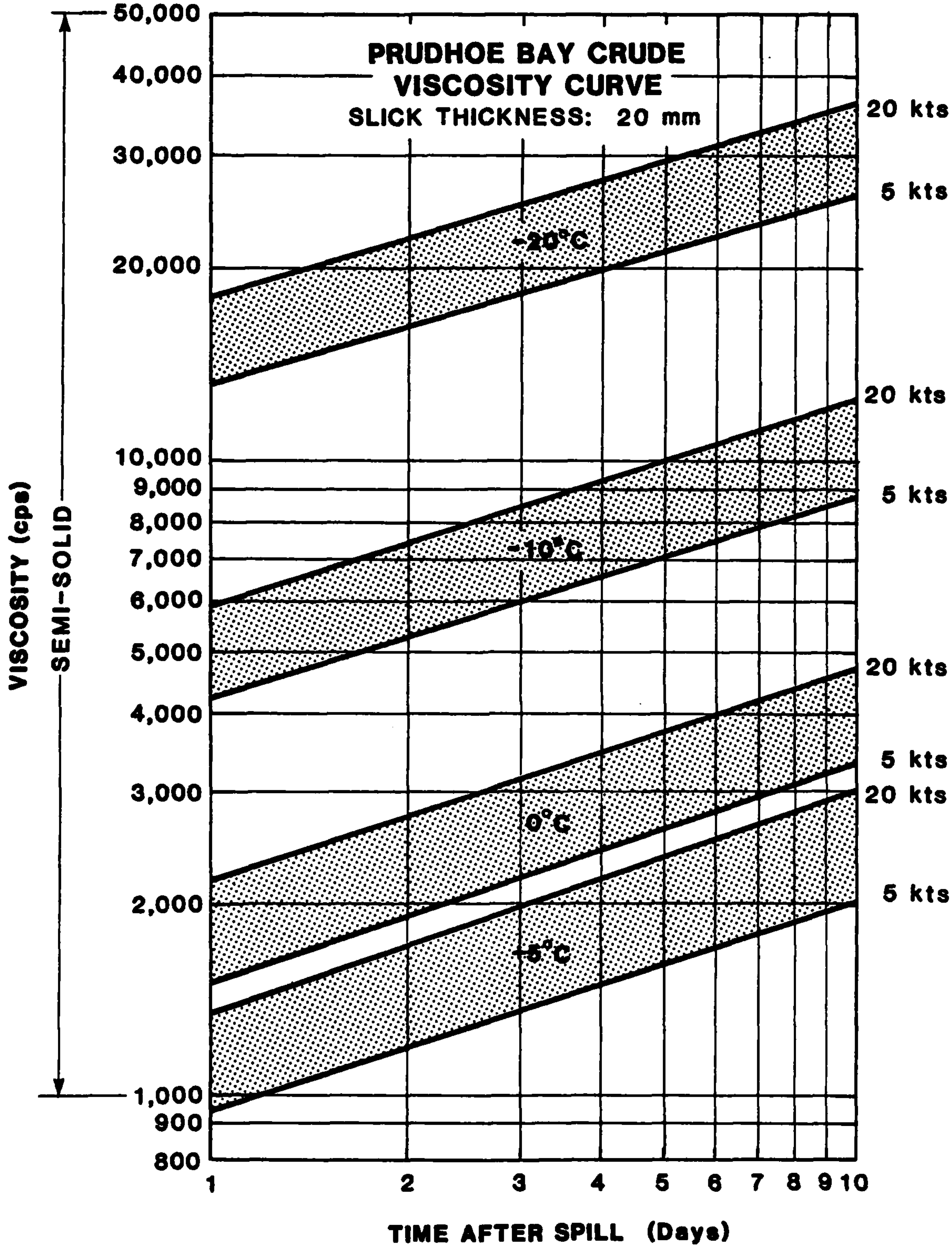


FIGURE 2.2.4 VISCOSITY OF PRUDHOE BAY CRUDE - 20 mm slick, days 1 through 10

hours the oil is exposed, particularly for the 5 mm slick. The word descriptions for viscosity, along the vertical axis of the curves show that the crude oil is thick to semi-solid at arctic temperatures even before the weathering begins. For all of the spill thicknesses, there is a general trend for the spilled oil to become semi-solid in the first day that it is exposed.

The curves show viscosity for wind speeds from 5 to 20 knots. Although the higher wind speeds increase viscosity, the effect of temperature on viscosity is much more significant. In the deep winter when temperatures are -20°C or lower, weathered crudes can be expected to be nearly solid. This result checks well with reports of operators on the North Slope. Most observers report that crudes exposed in the winter become tar-like in about three hours.

Also note the differences between viscosity for the various slick thicknesses. The viscosity of the thicker slicks remains low for a longer period of time.

Figures 2.2.2 through 2.2.4. show how viscosity changes after the first day. The viscosity continues to increase during the first 10 days of exposure so that the spilled product can be expected to vary from stiff to hard. As before, wind velocities affect viscosity, but temperature is much more important. Low temperatures produce a highly viscous product. Over the ten day period the thicker slicks do not become quite as viscous as the thinner slicks, but in every case, weathered arctic crude can be expected to be stiff.

Figure 2.2.5 shows the change in viscosity of arctic diesel as it weathers. Arctic diesel is a highly fluid, gasoline-like substance when it is spilled and remains in that condition after it is weathered. Arctic diesel is designed to remain fluid so that it can be used at very low temperatures, and it does retain these properties even after it has weathered.

2.3 Pour Point

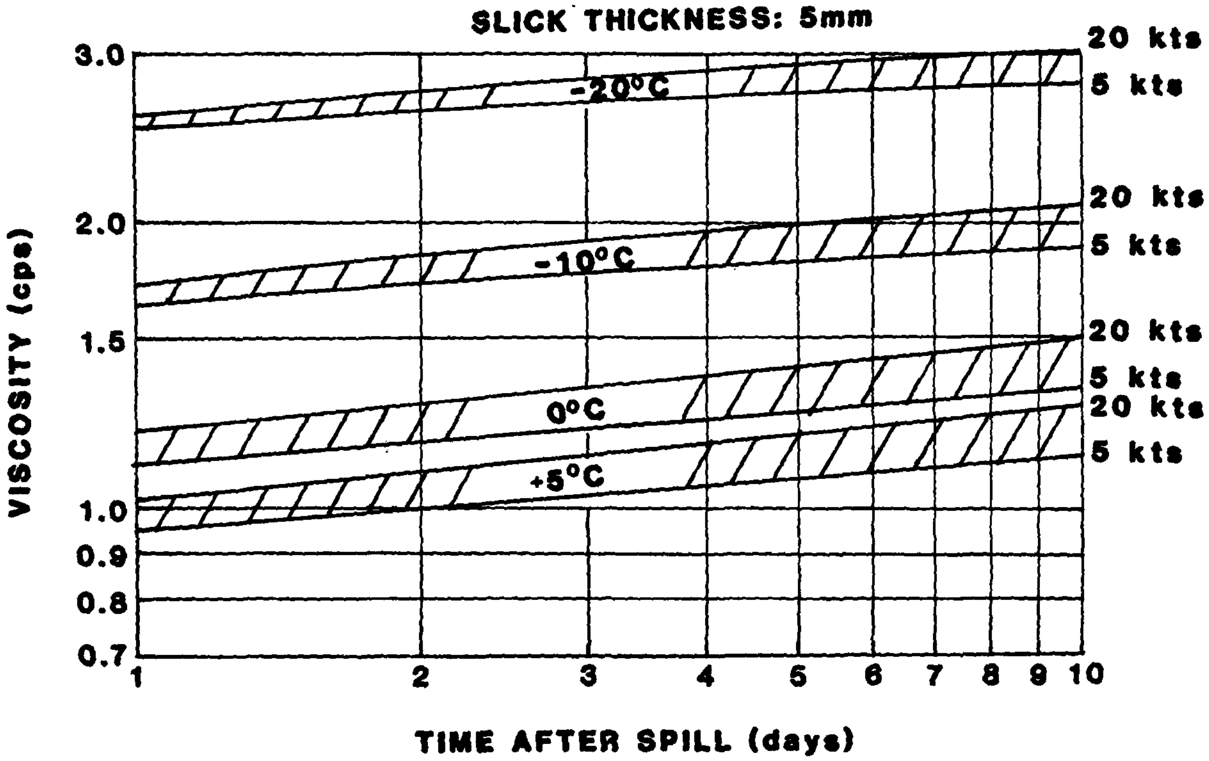
Pour point marks the place where oil behaves more like a semi-solid than a fluid (6). In laboratory tests to determine pour point, a sample of oil is placed in a test jar that is sealed with a thermometer embedded in the oil (7). The test jar is placed in a cooling bath, and at intervals the jar is removed from the bath and tilted to determine if the oil is liquid. At the point where the oil shows no movement, the test jar is held in a horizontal position for 5 seconds. The pour point is the lowest reading of the thermometer at which the oil shows any movement.

The pour point of fresh Prudhoe Bay crude is -9.4°C (15°F) (8). The pour point of this crude has not changed much over the years that it has been produced, and it is not expected to change as production continues. The pour point of other products taken from other locations could be different, however.

Figure 2.3.1 shows how the pour point of Prudhoe Bay crude changes with weathering. Notice how the pour point increases rapidly from -9.4°C for fresh crude to a value well above 0°C in less than a day. The curve is shown for a 5 mm slick because that is the expected terminal thickness of Prudhoe Bay crude on cold water.

The pour point of arctic diesel is quite another matter. Arctic diesel is a refined petroleum product that is designed to be used at very cold temperatures, so its initial pour point is very low and remains quite low even after the product

ARCTIC DIESEL



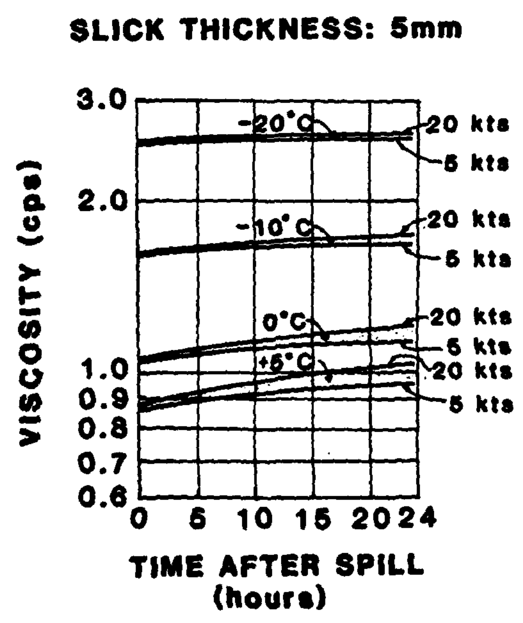


FIGURE 2.2.5 VISCOSITY OF ARCTIC DIESEL-
Slick Thickness of 5 mm

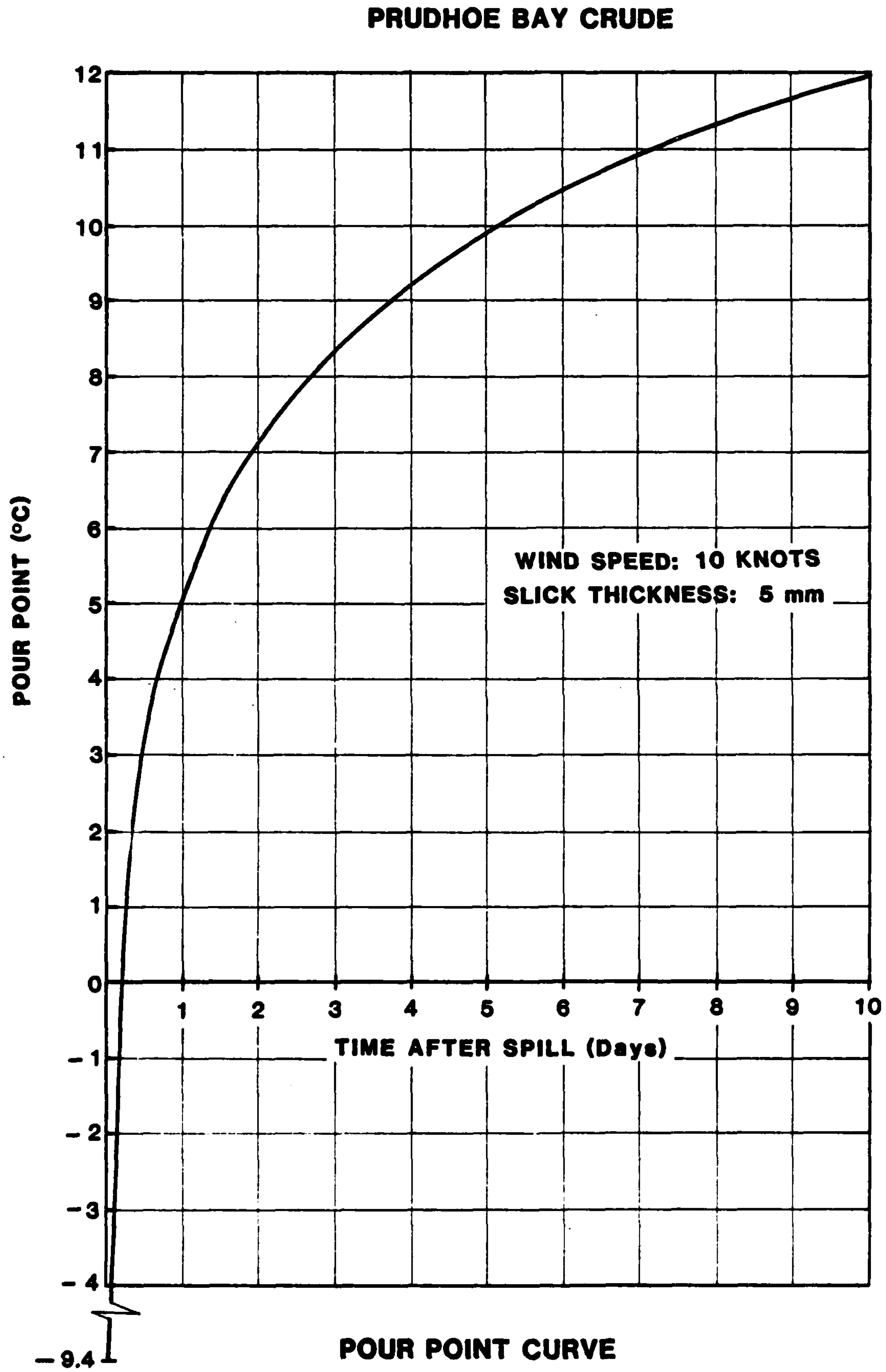
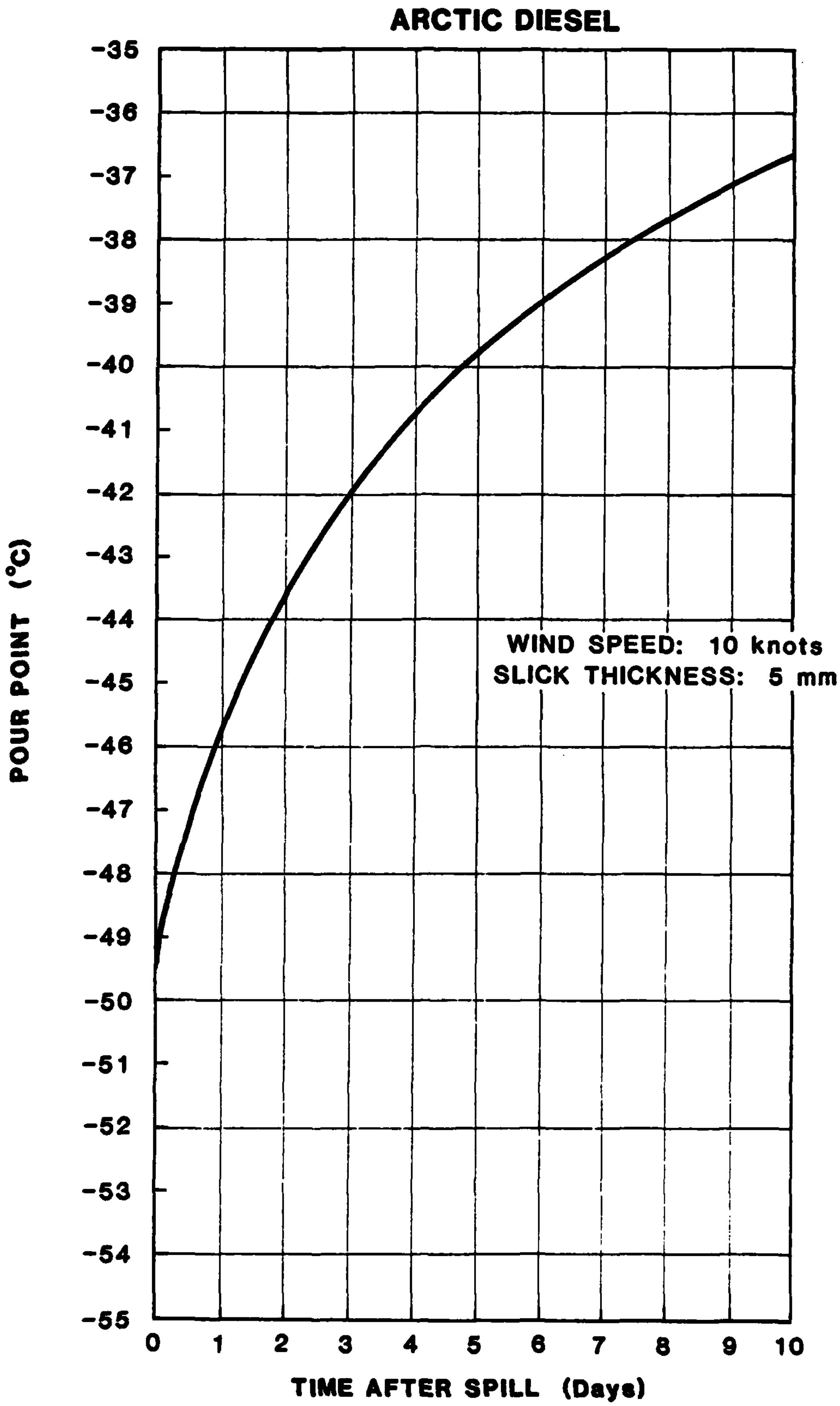


FIGURE 2.3.1 POUR POINT OF PRUDHOE BAY CRUDE



POUR POINT CURVE

FIGURE 2.3.2 POUR POINT FOR ARCTIC DIESEL

has weathered. The pour point of fresh arctic diesel is -51°C (-60°F) (9).

Figure 2.3.2 shows the change in pour point of arctic diesel as it weathers. The pour point increases rapidly during the first day of exposure, but the rate of change is not as high as for Prudhoe Bay crude. The pour point continues to rise over the 10 day period of exposure; however, even after 10 days arctic diesel is still fluid at very low temperatures.

2.4 Density

The density of a relatively heavy crude spilled on water is of more than casual academic interest. In some cases, density can be the most important physical property that affects spill behavior. To illustrate the point, consider the case of the spill of #6 fuel oil from the KURDISTAN off the coast of Nova Scotia (10). Of course #6 is a much heavier oil than crude, but after crude has weathered the densities of these two oils are nearly the same.

The KURDISTAN spill occurred in cold water and pack ice. The density of spill samples were found to be 0.987 g/cc, only slightly lower than the seawater, which was 1.028 g/cc, and higher than the sea ice, which was 0.917 g/cc. In this situation the positive buoyancy of the spilled oil relative to the seawater was only 0.04 g/cc. As a result, blobs and pancakes of spilled oil were observed to be easily carried under the water surface by winds and waves. Pancakes of oil were also observed to be awash, covered by a few centimeters of water.

Because the density of the spilled oil was <u>greater</u> than the ice, the spill particles could also be easily carried under the ice.

A rather dramatic example of oil sinking because of increased density occurred off the coast of Greenland. On August 5, 1977, the USNS POTOMAC was being escorted by the USCGC WESTWIND in intermittent dense fog through the scattered sea ice in the northeastern part of Baffin Bay off Greenland (11). At 0430 it was discovered that a tank containing about 380 tons of Bunker C fuel oil had been holed by an iceberg and almost all of the oil was spilled. The fate of the oil in these sub-arctic waters was not quite what one would expect.

Soon after the spill occurred, the oil took the form of small pancakes about 10 to 20 cm in diameter and 5 to 7.5 mm thick. These lumps of oil stretched out in windrows 4 m wide trailing a visible sheen bleeding from the edges.

Fourteen days after the spill, the oil could not be spotted from the air, but pancakes of oil were still visible from the surface in rows 70 to 100 m wide. By the fifteenth day, 80% of the pancakes were no longer bleeding and most of the volume of the remaining pancakes was submerged. There were many pieces of oil the size of cornflakes visible at the water surface and in the water column. The surface oil had become spongy but had not really formed a mousse. After several weeks it still had only 5% water content.

The oil did not reach the shore and did not contaminate ice bergs, possibly because melt water streaming down the face of the ice kept it away. The amazing part of the incident was that by the fourth week, <u>the spill was gone</u>. As the oil weathered it sank in the water column. The oil had a specific gravity of 0.96 g/cc when it was spilled, and as it weathered it must have increased to a density greater than that of the sea water, which was 1.024.

Except for some evaporation and the bleeding sheen, the entire spill sank in 1000 m of water off Greenland.

The point to be made is this. Although the density of fresh Prudhoe Bay crude is less than for #6 fuel oil, in 10 days it can have a density of 0.96 g/cc. After additional weathering, and possibly combining with near shore sediments, it could finally become more dense than seawater, sink, and become a nearly permanent deposit on the bottom.

In spill weathering tests performed at the Coast Guard R & D Center, Prudhoe Bay crude was found to have a density of 0.94 g/cc in a month and emulsified crude had a density of 0.98 g/cc (6). These weathered spill products could easily exhibit a behavior pattern similar to that reported for the #6 fuel oil from both the KURDISTAN and the POTOMAC.

Figure 2.4.1 shows a plot of the density of Prudhoe Bay crude based on the physical properties model. The plot is for a slick thickness of 7 mm because this is the best estimate for the terminal thickness of crude spilled in a broken ice field. (Note that this terminal thickness is slightly more than the estimated terminal thickness of 5 mm on open water.) A temperature of 0°C is used because the principal interest is for oil on water, and the water temperature is expected to be very close to freezing.

Although there is no rapid increase in density when the oil is first exposed, the increase is steady and is likely to continue. The density of the spilled crude is greater than the normal density of sea ice as soon as the spill is in the water, and as time goes on, the reserve buoyancy of the viscous globs of oil would be very low. The oil could be expected to be awash sometimes and could easily be carried under the surface of the water by winds and waves.

Figure 2.4.2 shows the density of arctic diesel as it weathers for a period of 10 days. A thickness of 5 mm is used to represent an accumulation of the spilled product in ice. If the arctic diesel were permitted to spread out to terminal thickness, density would not be an issue.

The curve shows that density continues to increase with time and that high winds significantly increase density. In spite of the increases because of weathering, the density of the diesel remains rather low. Since the density is much lower than sea ice, the spill is less likely to be swept under the ice. In addition, the density is much lower than the sea water, so the spill should float easily even after it has weathered for a long period of time.

2.5 Solubility

Solubility is defined as the amount of a substance that can be dissolved in a solvent under specified conditions. The solubility of hydrocarbons in water is quite low, in the range of fractions to tens of parts per million (ppm). Further, the solubility of hydrocarbons in cold arctic waters is less than in warmer waters by about a factor of ten. As a result, the behavior of petroleum spilled in arctic waters is not significantly affected by solubility, and there is no measurable loss of spilled products caused by dissolution.

Even though solubility has virtually no effect on the spill response effort, dissolution of hydrocarbons in water, even in very small quantities, may have an important affect on biological communities in the water. This section will therefore provide some basic information so that the OSC will have a general idea of how much

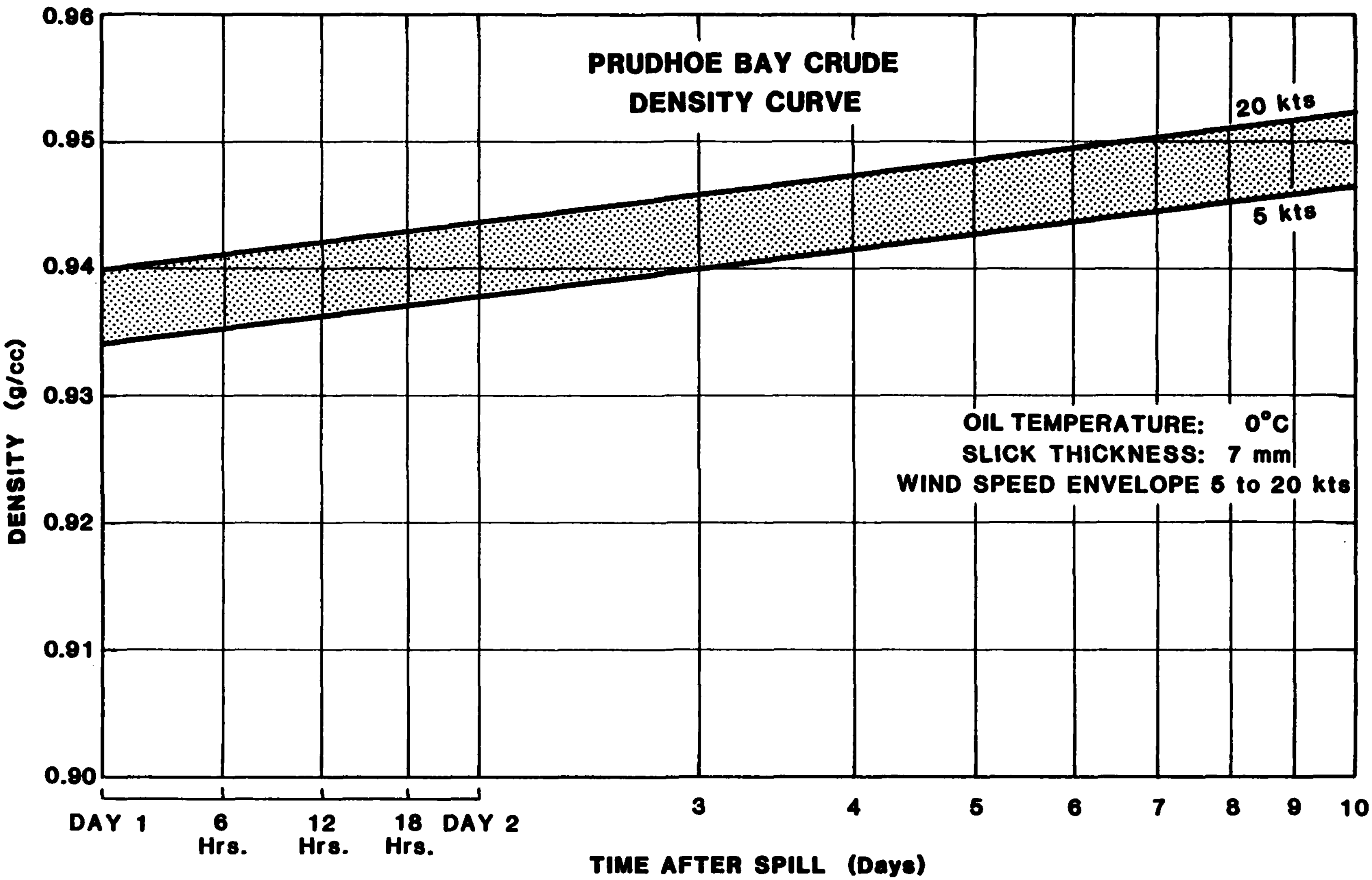


FIGURE 2.4.1 DENSITY OF PRUDHOE BAY CRUDE. The ordinate at day 1 shows density at the end of 1 day of weathering.

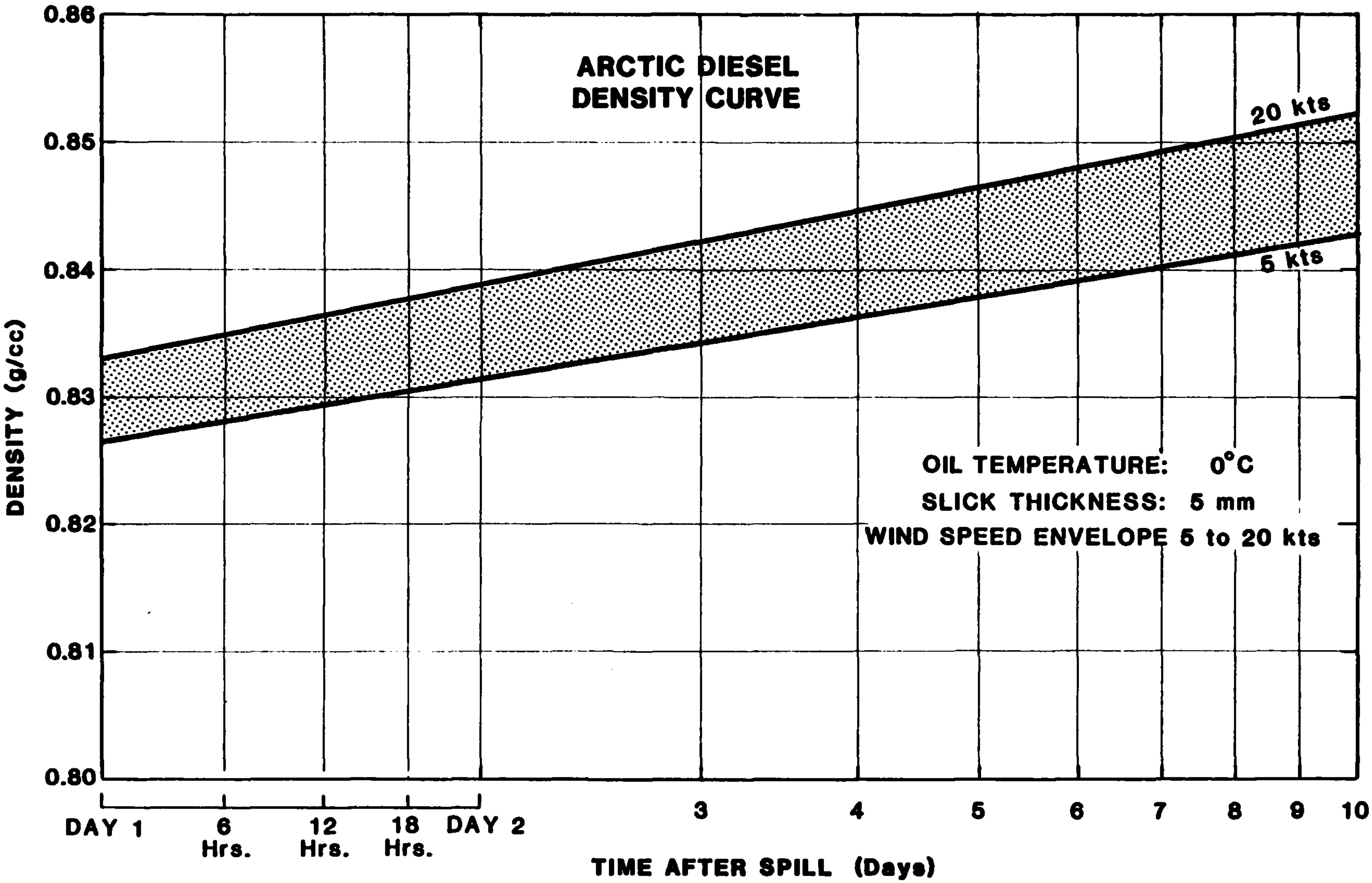


FIGURE 2.4.2 DENSITY OF ARCTIC DIESEL. The ordinate at day 1 shows density at the end of 1 day of weathering.

dissolution may be resulting from a spill.

First it is important to realize that evaporation and solution are simultaneous and competitive processes (12). Volatile hydrocarbons evaporate and go into solution at rates that depend on their vapor pressure and solubility. For example, evaporation of aromatic hydrocarbons is 100 times the rate of solution, and evaporation of alkanes is 10,000 times solution. Available evidence seems to indicate that if hydrocarbons dissolve in water under a spill, they do not remain in solution long. McAuliffe reports that in a 1977 ocean test spill of crude oil, dissolved hydrocarbons were not found in near-surface water (1.5 m depth) 15 minutes or later after the oil discharges (12). The reason for this appears to be that hydrocarbons dissolved from the surface slicks quickly evaporated.

Another reason for the extreme variability in the evaporation and dissolution processes is the variablity of the spill environment. Oil discharged on the surface of the water is in a constant state of flux between solution and evaporation. Currents and waves continually renew the water under the slick and provide new water in which the oil can dissolve. Similarly the wind over the slick is not saturated with hydrocarbons and provides new opportunities for evaporation. The movement and mixing of the waves gives the oil that has dissolved in water extensive exposure to the air for evaporation. Because of this mixing and exposure, most evidence indicates that oil that dissolves in water evaporates quickly.

A subsurface discharge of oil would provide the greatest opportunity for hydrocarbons to dissolve in water (12). Also, if oil penetrates beach sands or marshlands, the interstitial water will have an opportunity to approach equilibrium with soluble hydrocarbons present in the oil (12). The amount of soluble hydrocarbons available for dissolution can vary widely, and depends on how much of the oil has weathered before becoming incorporated into the sediment.

In 1973 Environment Canada sponsored a series of laboratory tests to determine the solubility of crude oil and refined products in water (13). These tests were performed in closed containers and water samples were taken immediately after mixing the oil in water, therefore the oil was not permitted to weather (i.e., evaporate). In these tests it was found that a mixed blend of crude dissolved up to 44 ppm (g/m^3) at 25°C. The oil went into solution fairly rapidly over a period of two days then the amount that was in solution remained nearly constant.

In the same tests #2 fuel oil dissolved up to 7 ppm in a period of 4 days then remained constant.

These tests do not have much direct application to an oil spill situation except that they show that crude oil is more likely to dissolve than a refined product. Dissolution in arctic waters at about 0°C can be expected to be much less than in laboratory conditions with water at 25°C. Also in the field dissolution is not likely to persist because of the evaporation stimulated by winds and waves.

Figure 2.5.1 shows the solubility of a 7 mm slick of crude in seawater at 0°C in a wind of 10 knots. A 7 mm slick was selected because it is a likely terminal thickness for crude spilled in broken ice. The curve shows that solubility values are much less than those recorded in laboratory tests at room temperature. Further, the curve shows that solubility decreases fairly rapidly with time.

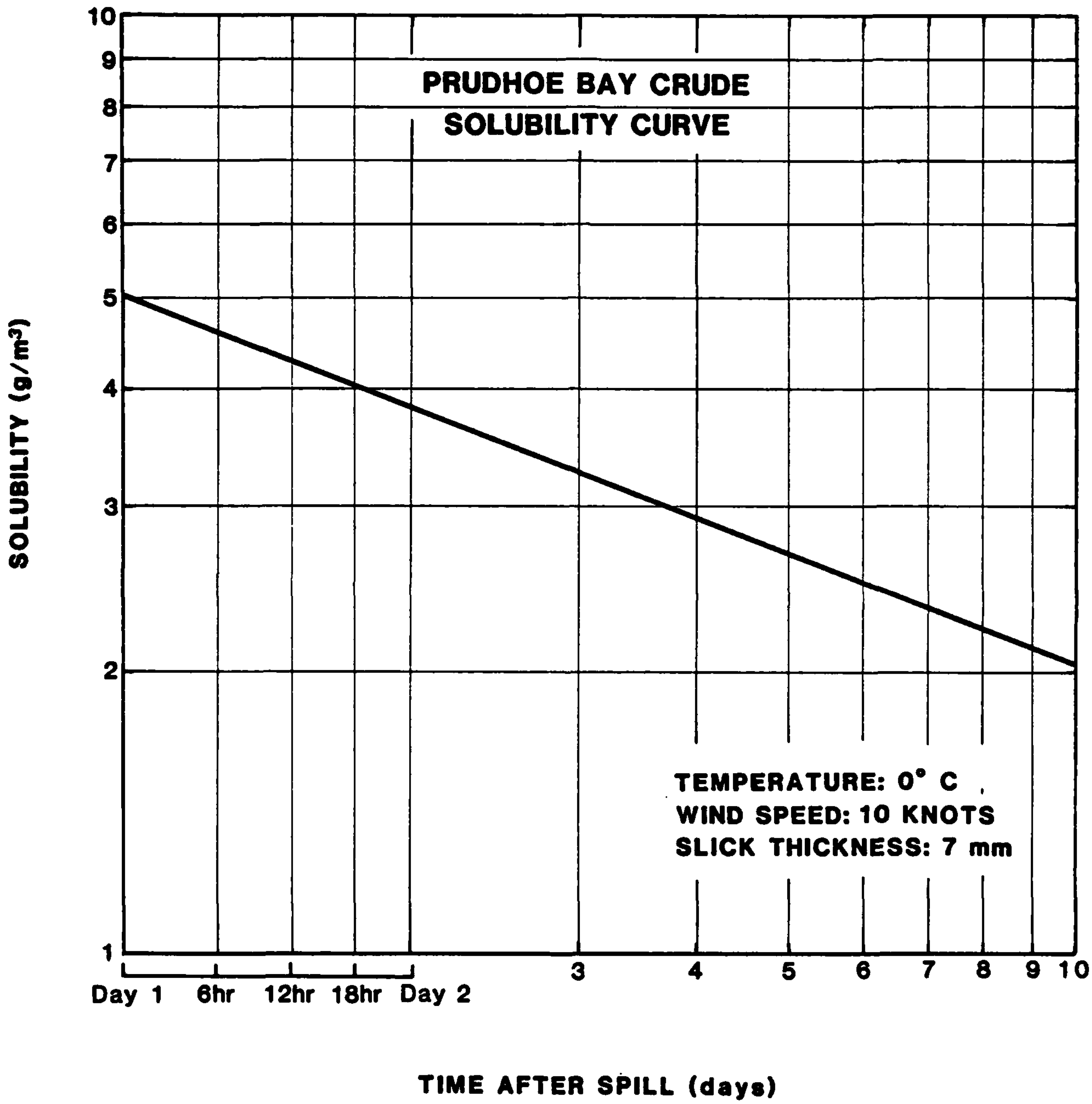


FIGURE 2.5.1 SOLUBILITY OF PRUDHOE BAY CRUDE. The ordinate at day 1 shows solubility at the end of 1 day of weathering.

Figure 2.5.2 shows the expected solubility of arctic diesel in cold seawater. As expected, solubility is lower than for crude and solubility decreases appreciably with time.

2.6 Dispersion

Natural dispersion of spilled oil refers to the tendency of small particles to move down into the water column and remain in suspension. It does not include the case of large globs of oil sinking because of high-density, or large amounts of weathered oil being transported by subsurface currents.

Natural dispersion is a phenomenon that presumes a large amount of wave energy is available to drive the particles of oil down into the water column. The waves must be present and must continue in order for the dispersion to persist. This is because the low density of spilled products will cause them to rise and come out of dispersion just as soon as the source of energy is removed.

Natural dispersion has not often been documented in spill situations. There are probably several reasons for this. One reason is very practical: dispersion occurs below the surface of the water and therefore it is not likely to be observed unless water samples are being taken at a variety of depths. Even if samples are being taken, the data rate is bound to be very low because information is only available at the sampling stations.

In spite of these problems, there is some documentation of dispersion in actual spills. One report describes the behavior of #6 fuel oil that was spilled from the tanker ARROW (14). The ARROW broke up in the stormy waters off the coast of Nova Scotia, where wave heights outside Chedabucto Bay were seldom less than 1.2 m and often reached a height of 6 m.

There was some natural dispersion in this case. Subsurface oil particles were observed, ranging in size from 0.1 mm to 2 mm, and were found down to a depth of 50 m. The maximum concentration of these particles was 0.02 ppm, and the concentration decreased with depth. At one point these particles formed a tongue outside the bay that was 7 miles wide and 45 miles long. The study was not able to estimate the amount of oil that was removed from the spill by dispersion or the effect of this oil on the environment.

This rather dramatic example of natural dispersion can be explained, at least in part, in terms of two special spill conditions.

First, the spill was #6 fuel oil, and by the time the dispersion was reported, the oil was well weathered. These small oil particles, therefore, probably had a very high density, so that sinking may have contributed as much to the distribution of the oil in the water column as dispersion. Even high energy waves would not have driven as much of a lighter product into the water column.

Second, high wave energy was important to dispersion after the ARROW spill. Arctic areas are not likely to have 1.2 m waves and definitely will not have 6 m waves; therefore, the conditions that contributed to dispersion in the ARROW spill are not likely to occur in the Arctic.

Laboratory tests of spill dispersion confirm what one would assume to be true concerning the natural dispersion of light products; that is, they tend to come out of dispersion as soon as the source of energy is removed. In tests performed in 1980 for the Alaska Oil and Gas Association, Cox found that the dispersed particles were very buoyant. They continually

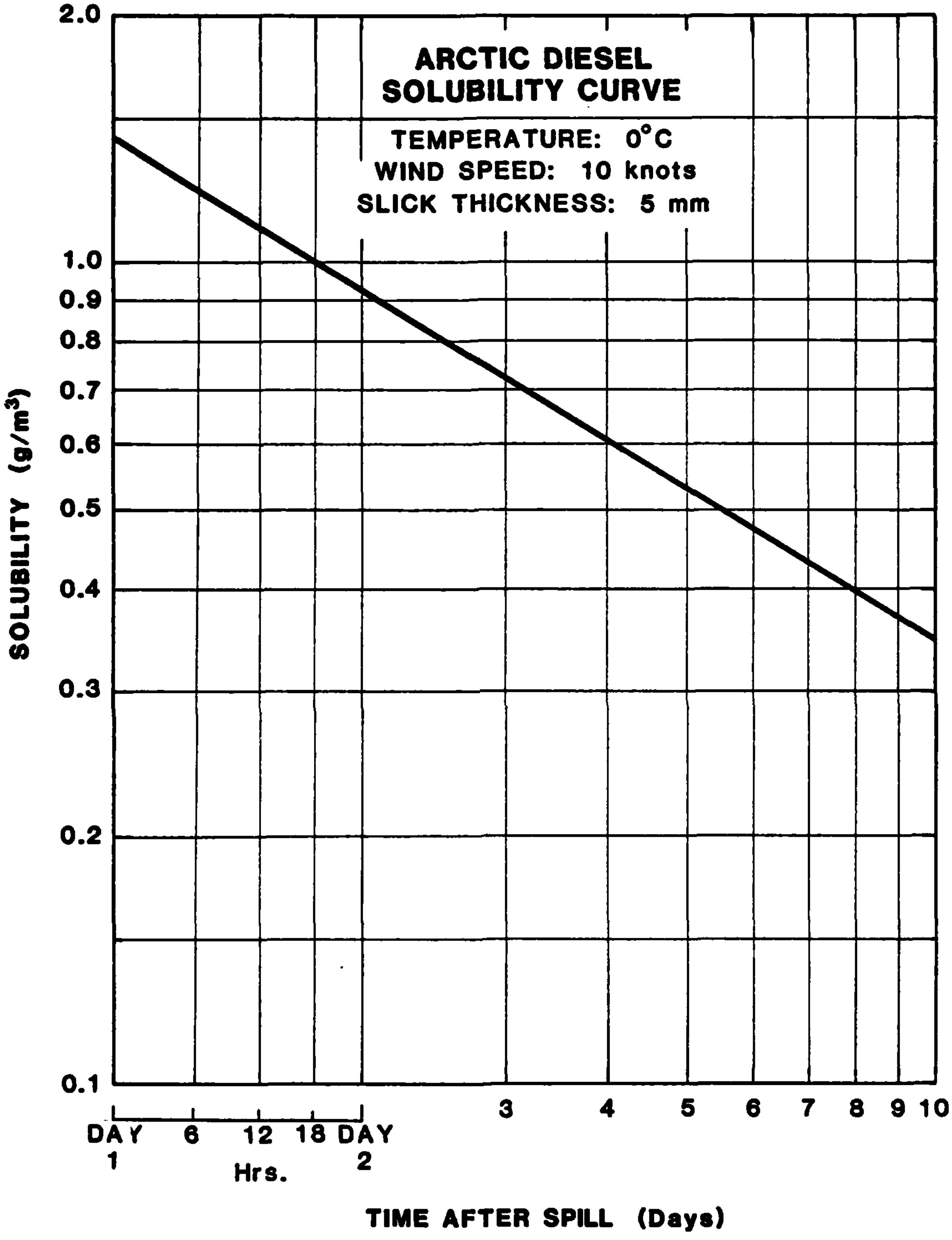


FIGURE 2.5.2 SOLUBILITY OF ARCTIC DIESEL
The ordinate at day 1 shows the solubility at the end of 1 day of weathering.

resurfaced during the test and were then remixed by a mechanical energy source (15). When the energy input stopped, dispersion immediately went to zero. These tests suggest that this behavior may also occur in the field. Significant transient natural dispersion may occur in the ocean in the upper few centimeters of water, but just as in the tests, this dispersion is not likely to persist after the wave energy is removed.

Natural dispersion is not likely to be an important behavior pattern for hydrocarbons spilled in the Arctic because the sea states are generally low. If some distribution in the water column does occur, the process is more likely to be one of suspension, subsurface floating, or sinking rather than real dispersion.

2.7 Combustibility

The idea of spill disposal by in situ burning has become popular for remote offshore arctic regions because most means of mechanical recovery are not likely to be effective in ice. However, in spite of some advantages of in situ burning, there is also concern about the fate and effects of the residue of burning.

Laboratory and field tests show that residue of a burn may amount to between 5 and 50% of the volume of the original spill. If the spill is large, the residues may also be large enough to result in a significant impact on the environment. Residues of crude oils are generally heavy and gummy. If the burning occurs on water or ice, the residues may finally sink to the bottom. The residues may also be very enduring. Whereas most spilled products will disperse and degrade in the environment, the residues of a burn may last 10 years or longer. If a burn is to be conducted on a shoreline, there are also concerns about damage to the permafrost layer and the vegetation.

The successful use of in situ burning in open water conditions depends on the way in which oil vaporizes and burns as a thin film on the water (16). It is therefore useful to begin with a brief description of the thin film burning process.

The combustion reaction occurs after the fuel is vaporized and the vapor is heated to a temperature at which it will react when mixed with oxygen from the air (17). Figure 2.7.1 shows the combustion process for liquid fuel floating on water. The combustion reaction and the release of heat occur at the flame front. Air is transported inward from the periphery by convection while back-radiation from the flame vaporizes additional fuel to maintain the process. The fuel-vapor interface is at the boiling point of the liquid fuel, while the fuel vapor area is between the boiling point of the fuel and the flame temperature. The temperature of the water just below the fuel is between the boiling point of water and the ambient temperature of the seawater, generally near -2°C in the Beaufort Sea.

The water acts as an infinite heat sink taking heat away from the fuel. As the layer of burning fuel becomes thinner, the heat conducted away by the water nearly equals the heat back-radiated by the flame. At this point the rate of burning and the height of the flame both moderate. As the fuel layer becomes thinner, a temperature is reached at which there is no longer enough fuel vaporization to maintain the flame in competition with heat losses to the water. When the liquid fuel reaches this temperature, known as the fire point, the fire goes out. This is an important point because most problems with in situ burning result from attempting to burn a slick that is too thin.

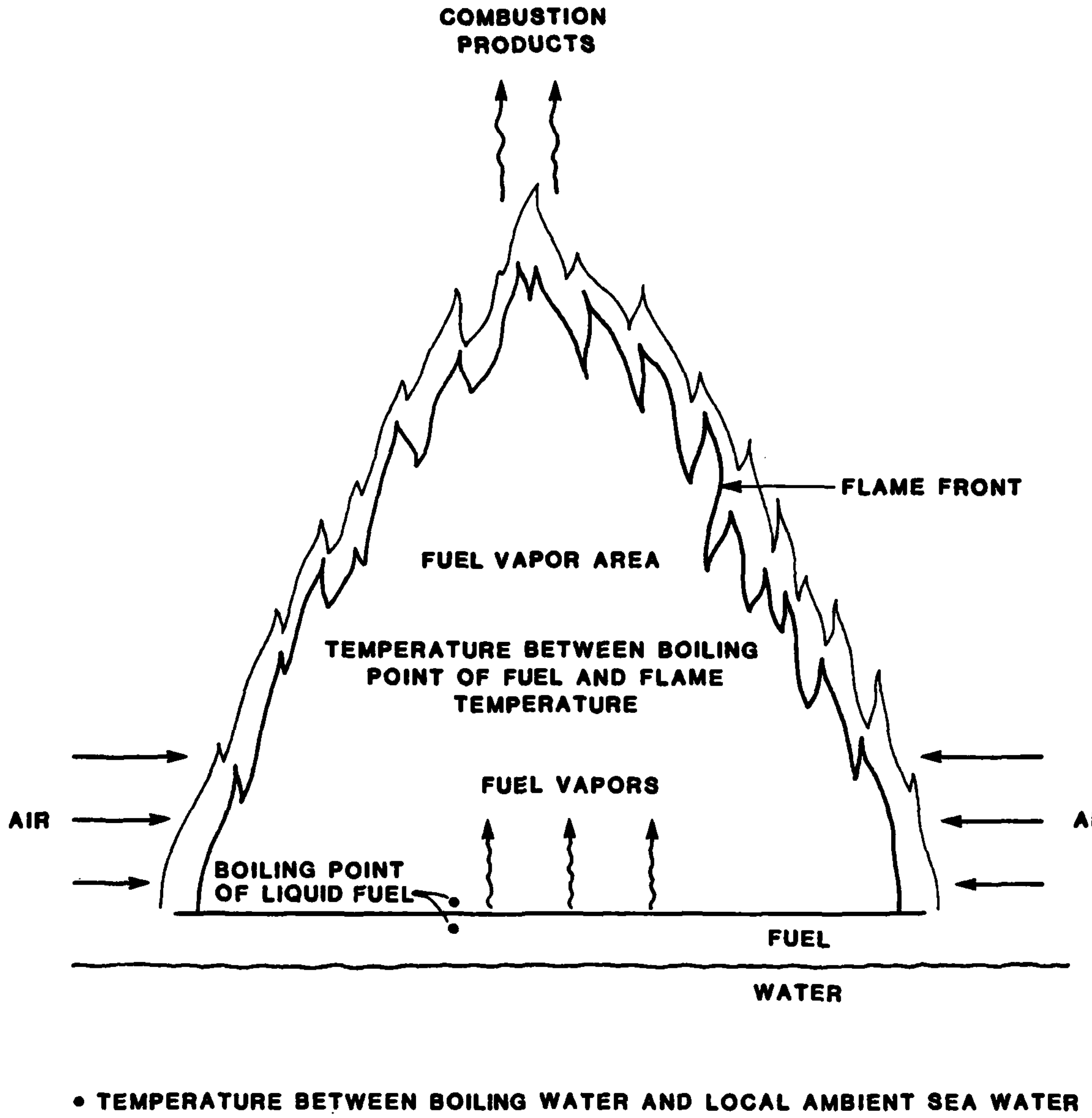


FIGURE 2.7.1 COMBUSTION OF OIL ON WATER

The fire point is a characteristic of the fuel. Some light hydrocarbons have a fire point below 100°C, so that in theory these fuels should burn away completely. For crude oil, the boiling point and fire point of the residual material remaining at the end of combustion is greater than 100°C. Most crude oils burn out when the layer thickness goes below 5 mm (2), although in some cases burning may continue down to a thickness of 2 mm.

Fresh crude oil contains light ends that give it an initial fire point below 50°C. The fire point is much higher if the material has weathered, and it rises during burning as the lighter materials are vaporized.

Except for the brief open water period in the summer, oil from an underwater blowout will be mixed with ice. Field tests show that the ocean surface above a blowout will have a ring of waves concentric with the plume center. This ring marks the place where outward flowing currents inside the ring meet with inward flowing currents that occur outside the ring (18). It seems likely that this wave ring will form a natural containment barrier of ice with a clear area in the center. At first the oil will be concentrated in the center of the plume and then will gradually work its way out through the channels between ice pieces outside the wave ring zone. In theory, the oil at the center of the plume should be thick enough to support combustion, and burning will prevent it from migrating between the pieces of ice away from the central area. This action, of course, is only recommended when the plume is a safe distance from the drill site, associated equipment, and personnel.

As a corollary, it seems reasonable to believe that oil in deep pools between ice floes could also be burned. These channels could provide protection to prevent the flame from being extinquished by gusts of wind.

Burning has not been used often as a spill response measure outside the Arctic because of possible safety problems and because burning generally produces unacceptable levels of air pollution. As a result, there is little experience to show how burning should be employed or the circumstances in which it would be effective. Most of the information about *in situ* burning comes from field tests and laboratory tests. These tests are therefore used to describe the combustibility of spilled products and the expected behavior of oil in burning operations. The few cases in which burning has been used as a spill response measure are also described.

2.7.1 Arctic Summer Burning Tests

The U.S. Coast Guard conducted spill response tests in the Chukchi Sea in the summer of 1970 (2). *In situ* burning experiments were performed during these tests using Prudhoe Bay crude oil. Oil was released on ice and on melt ponds. The burning tests were run both with fresh oil and with oil that had aged up to six days. Fumed silica, glass beads, and straw were tested for promoting combustion. In all cases a lighted, diesel soaked rag was used for ignition.

Both fresh and aged crude ignited quickly and burned vigorously. Even when lighted on the downwind side, the flame spread quickly upwind until the entire pool was burning. When the burn was performed on ice, the heat of the fire formed channels permitting melt water and burning oil to drain to lower levels. All burns produced heavy, black smoke, but no soot was found on the ice in the area of the burn.

Winds during the burns were

calm to 14 knots. In these conditions a test spill of about one barrel of oil burned in 8 to 14 minutes. (This is a burn rate of about 4 gallons per minute which is equivalent to a rate of about 130 BBL per day. This is a far more conservative estimate than the 3.8 million barrels a day that could be assumed from a burn rate of 1.5 mm/minute.) The residue from the burns was estimated to be 2 to 10% of the original volume. It is important to note that the slick thickness for the test burns varied from 16 to 95 mm. This is significant because a burn of a much thinner slick may be less successful.

Burns were also made in a number of different environmental situations: fresh crude on water, fresh crude on ice, aged crude on water, and aged crude with various agents designed to promote combustion. The combustion promoting agents did not affect burning performance and were not needed, probably because the burns were made on relatively thick accumulations of oil. These tests were just a first look at in situ burning as a spill response measure, but they showed that burning definately has potential for success.

2.7.2 Arctic Winter Burning Tests

The Coast Guard conducted arctic winter spill response tests at Port Clarence, Alaska during January and February of 1972 (19). Part of the experimental program included in situ burning tests of Prudhoe Bay crude.

The winter tests showed that burning works best when the oil is less than 24 hours old. The best burns were on spills that were at least 6 mm thick and in winds of not more than 14 knots. The temperature of the air or the oil did not seem to affect the intensity of the burn, but winds greater than 14 knots tended to knock flames down and blow loose snow into the oil, cooling it below ignition temperature.

Oil burning on snow tended to melt pits through the snow over the hottest areas of the burn. The pits were 10 to 15 centimers in diameter and 15 to 20 centimers deep. The intense burning at the bottom of the pits melted the adjacent oiled snow and permitted the oil to flow down into the pits for burning. At the end of the burning tests the pits were up to 1 meter in diameter and 1/2 meter deep. Oil on the snow surface not immediately adjacent to the pits cooled and stopped burning. Because of this, burning on snow seemed to be less effective than burning on ice. During these tests 95% of the oil in the pits was burned, but only about 30% of the oil on the surface was burned. The overall burning efficiency was about 70%.

Burning oil on ice seemed to be easier than burning on snow (19). When the oil was about 6 mm thick, the entire pool burned and sustained combustion. As the fire became intense, a thin layer of ice melted and formed a 6 mm pool of water under the oil. The water seemed to insulate the ice below from the burning oil. The oil floating on the layer of water was also free to flow, so that if the ice is not level, the burning may cause the oil to spread and contaminate a larger area.

The burn on ice was estimated to be about 90% effective. The residue of the burn, however, was a thick tar on the melted ice. In a short time the water re-froze encapsulating the tar. This, of course, would complicate the removal of the tar.

Three burning agents, 1) silicate beads, 2) asbestos powder, and 3) powdered calcium carbonate, were spread on the fresh oil on ice to investigate possible changes in burning efficiency (19). As in the summer

tests, the agents did not improve the effectiveness of the burn, and some agents left additional residue that complicated the final cleanup effort.

The winter tests showed that oil only burns on snow and ice if it is free of snow cover. Once the snow covers the oil and forms a mulch, it is difficult to ignite the mixture or sustain a burn. Burning must therefore begin before snowfall or before high winds result in blowing snow.

2.7.3 Spring Burning Tests

A set of highly comprehensive spill behavior tests were conducted in the Canadian Beaufort Sea in Balaena Bay near Cape Parry during the winter of 1974-1975 (3). These tests were the first major field experiments to determine the behavior of oil in ice, and they remain as probably the most important work that has been done to date. During these tests oil was released under ice in the fall and was left in place until it migrated to the surface in the spring. The burn tests, therefore, were performed on oil that had been encapsulated in ice all winter and percolated to the surface in the spring. These tests were therefore much more realistic than any that had been performed previously.

By the time the burn tests were conducted in June, 31% of the surface of the ice was covered by oiled melt pools and 16% by oiled snow. About 4800 gallons (114 bbl) of oil were available for burning. The maximum film thickness was 15 cm. Most of the pools of oil were interconnected by channels that were 30 cm deep in some areas. The uncontaminated snow was very wet and effectively contained the oil.

As the burning tests began, there was some concern about being able to ignite the oil because it had weathered for so long. These fears proved to be unfounded because even in mid-July the oil was ignited by a small paper towel soaked in gasoline. On thinner films of oil, a piece of sorbent was more effective in initiating combustion.

Burns were performed in winds of about 4 kts. The pools burned for about 30 minutes and the fires often spread between adjacent pools. It was estimated that about 90% of the oil that had surfaced was burned.

Heat from the burn caused oil entrained in the snow to flow into the burning pools. Although some of the burning pools were enlarged, the burning did not melt as much snow as expected. In most cases, snow was 30 to 40 cm higher than the pools. Observers also noted a cracking sound during the burn suggesting that the water was boiling or the oil was atomizing.

Melt pools that initially had a thick accumulation of oil were quite clean after the burn. Generally only a thin film of oil and residue remained on the downwind side. Globs of oil and small pools of residue varying from a grease-like substance to heavy tar were found on the surrounding snow. Some residue had a surface film strong enough that the residue could be lifted off the water by a corner. In areas where the burn was not complete, the remaining oil was viscous but still fluid with an average thickness of about 5 mm.

By mid-June the oil continued to move up in the brine channels. Of the 1100 gallons that was available for combustion, about 50% was burned. In this test the flame did not spread and each pool had to be ignited separately. The residue of these burns was very viscous and would not support combustion.

The Balaena Bay tests showed that *in situ* burning could be effective (3). Oil exposed on the surface for up to 6 weeks could be ignited if the film was at least 5 mm thick. With ideal surface conditions and proper timing, 80% of the oil spilled on ice could be burned easily. Disposal of the residues of the burn would be time consuming and labor intensive. Because of the differences in ice conditions, it would be difficult to accurately predict the effectiveness of *in situ* burning in dealing with a spill. The Balaena Bay tests, however, conclude that with reasonable care and unlimited resources, no more than 70% of the oil could be burned in fast or stationary ice, and possibly 30 to 40% in the moving pack (3).

2.7.4 Other Burning Tests

Several other spill behavior field experiments investigated the combustion characteristics of spilled products in arctic and cold weather conditions. These include tests performed by, 1) Dome Petroleum in the Beaufort Sea during two winters, 2) Energetex Engineering in southern Ontario, 3) Coast Guard Research and Development Center, 4) Alaska Oil and Gas Association, and 5) the Environmental Protection Agency (EPA) Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) facility.

First consider the tests performed by Dome Petroleum in the Beaufort Sea (20). At three different times during the winter, samples of Prudhoe Bay crude (mixed with compressed air to simulate gas) were released under ice. The oil came to the surface in varying patterns, depending on the oil/gas ratio, and became encapsulated in the ice. The burns, therefore, were performed on oil that had become encapsulated in the ice at varying stages of ice growth and had moved up in the ice to be released at the surface in the spring. A total of 125 burns were conducted using pyrotechnic igniters dropped from a helicopter. The helicopter drop accuracy was 80% and the ignition success was 94%. Considering these two parts of the operation together, the overall success rate was 75%.

The pyrotechnics easily ignited three week old slicks. Oil that was pooled on the ice burned much better than oil that came up through the ice in the form of droplets. Since the oil pooled on ice migrated vertically from areas where blowout products pooled under the ice, burn efficiency can be linked to gas flow at the blowout. A high gas flow causes the oil to disperse under ice over a wide area in droplets. When these light accumulations come up through the ice, they do not produce pools of oil that burn well. Conversely, when there is less gas flow in the blowout, the oil is not well dispersed and migrates to the surface to form pools that burn easily.

Burning efficiencies did not vary much from site to site, which indicates that the burn efficiency depends more on the slick thickness than on on the pool area, volume or oil age. (The slick thickness for the burns was not reported.) Burn efficiencies in these tests varied from a minimum of 15% to a maximum of 93%. Average burn efficiencies were from 77 to 82%.

In the winter and spring of 1982, Dome performed additional combustion experiments in the Canadian Beaufort Sea, this time using emulsions developed from Prudhoe Bay crude (21). The emulsions were deposited under the ice in mid-winter and allowed to surface during break-up. The burn tests were performed on the surfaced emulsions.

In the first test, the emulsion was ignited with a gasoline-soaked

sorbent pad, but the igniter was not effective. The fire went out as soon as the gasoline was consumed. On the next test a diesel-soaked pad was used. This worked much better because the diesel burned hotter for a longer time. The heat from the diesel igniter was enough to break the emulsion on the surface. This released the crude oil, which then burned. In these tests about 50% of the oil that had been in the form of an emulsion was burned. The burn efficiency from the individual test pools ranged from 14% to 63%. The report notes that emulsions samples had to be ignited at least twice as many times as samples of crude to achieve combustion.

An objective assessment of the Dome experiments show that water-in-oil emulsions of crude can be burned in situ, but many more ignitions are required and the burn efficiency is much lower than for a comparable amount of unemulsified crude.

Energetex Engineering of Waterloo, Ontario performed some burning tests for Environment Canada that provide some additional information on cumbustibility of petroleum products (7). Their tests were performed in the winter in Ontario using marine diesel, two Canadian crudes, and #6 fuel oil.

The Energetex tests tend to confirm and expand on the information already available from other field tests. Energetex found that in situ combustion is possible for confined slicks of all the oils tested even when these oils are aged up to three weeks. For a given oil type, the minimum thickness of oil that can be burned depends on the intensity of the ignition source. The minimum thickness that could be ignited for layers of aged crude oils and marine diesel ranged from 3 to 4 mm using a solid fuel pyrotechnic igniter and adding fresh crude to assist in ignition. It was estimated that 5 mm would be the minimum thickness that could be ignited without using fresh crude to help to start it off. Bunker C was burned with the solid fuel igniter aided by fresh crude at thicknesses of 4 to 5.5 mm. If fresh crude were not used they estimated that a 10 mm slick of Bunker C would be required for ignition. The thicknesses of the residual oil layers remaining after the combustion of the crude oils and diesel fuel ranged between 0.3 and 0.85 mm, while the residuals from burning #6 fuel oil were 1.6 to 2.6 mm thick.

Laboratory tests performed at the Coast Guard R & D Center show that highly weathered oils require greater ignition times and energies, produce lower oil and flame temperatures, burn for a shorter time, and usually burn less efficiently than less weathered oils (6). (The decrease in burn time and burning efficiency did not follow the trend reported in some earlier burning tests performed at the University of Toronto.) Tests performed with emulsified oils show that the higher water content results in more difficult ignition, shorter burn times, lower burn temperatures, and lower burn efficiencies.

The Coast Guard tests also noted changes in the flash point and fire point of the test products due to weathering. (The flash point of an oil is the lowest oil temperature at which a small test flame, swept across the oil layer surface, is capable of igniting the vapors at the oil surface. The fire point is the lowest temperature that results in burning that persists for at least 5 seconds.) The tests showed that the flash and fire points of #2 fuel oil increase only slightly with evaporative exposure. The flash point increased from about 110°C to 115°C. At the same time the fire point increased from 120°C to 130°C. For Prudhoe Bay crude, the flash point that began

at 100°C increased with exposure to a range of 125°C to 180°C. The fire point that began at 110°C increased to the range of 150 to 180°C, although it is likely that the increase in fire point resulted from the lighter ends of the crude being distilled out before the tests began.

Burn tests were performed on #2 fuel oil and crude oil. Of 14 samples tested, only four were successfully ignited (6). Since the slick thickness for the #2 fuel oil was 1.6 mm and the crude oil was 3.2 mm, this negative result tends to confirm the results of other tests that showed that a slick of at least 5 mm is generally required to support combustion. The tests also showed that Prudhoe Bay crude could be burned even after two weeks exposure in winter conditions if the sample is not emulsified.

Tests of combustion of oiled snow were conducted for the Alaska Beaufort Sea Oil Spill Response Body (ABSORB) in spring of 1981 (22). For these tests, Prudhoe Bay crude oil was applied to the surface of the snow by spraying. In one case the spray was applied to the snow just before the burn test and in another case the oiled snow was allowed to age for two weeks. In both cases, the oiled snow did not support combustion. The combustion continued only when the igniter melted the surrounding snow and released oil flowed down to the igniter. Localized combustion of the aged oiled snow was possible by igniting heavy concentrations of oil found in the low spots, but these fires did not spread. If the snow was pushed into a shape of a hollow cone, a fire could be maintained in the center. The melting snow permitted the oil to flow to the center and be consumed by the fire.

Recently spill burning tests were performed at the outdoor test basin at the OHMSETT facility, Edison, New Jersey (23). Prudhoe Bay crude was added to the test basin containing about 40% ice. With a water temperature of about 4°C and air temperature that varied from 5 to 8°C, the oil spread to a thickness of about 3 mm, which appeared to be equilibrium thickness both with and without waves. In these conditions, the oil burned with an efficiency that ranged between 83 and 95%. A preliminary (unpublished) report of these tests indicates that it is possible to start a burn on a 2.5 mm slick on cold water and burn it down to 1.5 mm (24). Similar results were obtained in another test in which an Alberta crude was burned down to a thickness of 0.5 to 2 mm (25).

There are very few cases reported in which <u>in situ</u> burning has been used as a spill response measure. Two will be mentioned briefly here.

In the 1977 Buzzard's Bay spill, some of the #2 fuel oil was destroyed by burning (5). First attempts to ignite the oil using a commercial wicking material failed. The wicking agent was then dipped in gasoline, and the treated agent successfully ignited the spill. An estimated 3,600 gallons of oil were burned in 90 minutes. The burn generated a considerable amount of black soot that was deposited on the ice for a distance of a few miles. <u>In situ</u> burning was dropped as a response measure because of the complaints of the local population about the black smoke.

Burning was also used for spill response in a Trans-Alaska Pipeline spill that occurred on frozen ground near Fairbanks, Alaska in February of 1978 (26). The contaminated vegetation and oil were pushed away from the pipeline and a small fire break berm was built to provide a buffer between the pipeline and the area to be burned. About 500 barrels of the spilled crude oil were collected

in this area for burning. Melting of ice and snow began as soon as the fire was started, so that this inland burn really occurred on a pool of water. The entire area burned for a period of about two hours. Later, oil that remained in isolated spots was burned over a period of about one week.

The oil burned easily on the water surface. As the water was heated from burning, globs of oil rose from the ground through the water column igniting with small explosions as they broke the surface. The burning pond enclosed by the berm had water depths ranging from a few centimeters to about one meter.

Some of the oil was burned on ice. Burning occurred rapidly with the heat rising so only minor melting occurred. When burning occurred on frozen tundra, the thaw went to a depth of several centimeters. Later in the summer the sheen that remained on the water surface was gathered with a surface collecting agent and recovered with a mechanical skimmer. In this case, <u>in situ</u> burning appears to have been a successful method of disposal.

Lewis postulated that an undersea blowout could probably be burned if winds do not exceed 15 miles per hour (27). In summer, winds are greater than 15 miles per hour 50% of the time, so as much as half of the oil could be lost without burning. Also, large, moving ice floes may extinguish the fire or may carry the oil out of the containment area. Since the rate of burning could possibly exceed the rate of oil supply, the spill area could be re-ignited periodically, which would reduce losses to burning somewhat. Lewis estimates that about 40% of the oil from the blowout would escape burning due to all causes.

2.7.5 Combustibility Summary

o Crude oil on water or ice will burn if it is at least 5 mm thick and winds are not greater than 14 knots. Under ideal conditions, a 2.5 mm slick may be ignited.

o Burn efficiencies of 70 to 90% can be expected in ideal conditions; in moving pack ice, burn effectiveness may be about 30 to 40%.

o Burns of oil on snow are possible if the oil is not coated with new snow. A light coating of oil on snow can be burned off if an igniter melts the snow so that the oil can pool in a depression in the snow.

o Residues of a burn are likely to be highly viscous and persistant. A burn of oil on ice will cause some melting, so the residues of the burn may freeze into the upper layer of the ice soon after the fire goes out. Residues of a burn of crude or diesel may be about 0.3 to 0.9 mm thick; residues of #6 fuel oil (or highly weathered crude) may be 1.6 to 2.6 mm thick.

o Oil-in-water emulsion can be burned with an efficiency of about 50%.

2.8 Emulsification

There are two kinds of emulsions to consider when dealing with oil spills. The first is the normal oil-in-water emulsion, which is simply suspension of oil droplets in water. Oil that has become emulsified in water is no longer a slick, but rather it moves with the water and mixes in the upper layer (29). This could be considered to be a beneficial emulsion because it has removed all or some part of the oil that was a surface contaminant and distributed it in the water column. Oil distributed in the water column is less likely to do damage to birds or shorelines and is more likely to degrade quickly

because of the increased surface area exposed.

Oil spills in high wave energy areas such as the English Channel have resulted in a water-in-oil emulsion, commonly called "mousse" because of its appearance (29). Water-in-oil emulsions may contain anywhere from 50 to 80% water and exhibit properties that are quite different from the original oil. Mousse has occurred during many major tanker spills, but it was particularly well documented in the AMOCO CADIZ spill that occurred along the coast of France.

Soon after the AMOCO CADIZ went aground, pools of floating mousse became the most common form of heavy oil concentration. The emulsion was generally brown to reddish-brown in color. The mousse was about 1 mm thick on the water, but accumulations up to 25 cm thick occurred on the shorelines. Nearshore samples appeared to be very stable and seemed to resist additional weathering.

The time required for mousse to form appears to be a function of the type of oil that has been spilled and the amount of mixing energy that is available. During the AMOCO CADIZ spill the mousse formed quickly. Oil appeared to change from the characteristic black to brown mousse in less than a ship length as the spill streamed from the hull. A sample collected next to the ship indicated that the change may have occurred even before the oil left the ship.

Although the mousse remains stable, it gives off a sheen with a thickness of about 10 microns that may be either light grey in appearance or have rainbow colors. It appears that the sheen is another form of fractionation with the lighter, lower surface tension components going into the sheen. Two weeks after the spill, weathered mousse had congealed into smaller globs. In this form it lost the well developed sheen it had when it was fresh.

Mousse is a totally different spill product from crude oil and likely to be difficult to deal with using conventional spill response equipment. However, extremely high wave energy conditions are required to form mousse, and these high energy conditions are not likely to occur in the Arctic, even during an underwater blowout.

This assessment was confirmed in some tests performed for Environment Canada that were designed to determine if stable emulsions are formed at the well exit during an underwater blowout (18). The tests were performed full scale to simulate the standard test blowout of 2,500 bbl/day with a gas flow ratio of 143:1. Seawater depths were 15 and 180 m and the pipe diameter was 15 cm.

These tests showed that when oil and gas are ejected from the well together, the oil appears to be drawn around the surface of the emerging bubble and then shattered into small droplets during the release and breakup of the bubble. These bubbles are carried up in the water column. The violent bursting action of the oil covered bubbles at the pipe exit produces a finely divided suspension of oil particles in the water. The nature of this splitting process is such that a continuous volume of water-in-oil emulsion is unlikely to be formed.

Because of the large volume of water that is entrained by the rising gas bubbles, the average density of oil in the medium is about one 1 mm droplet per cubic centimeter of water. It is therefore unlikely that these droplets would coalesce as they rise. Instead, the droplets could be expected to form a slick at the surface and additional mixing

energy would be required for mousse to be formed. Because energy is required on the surface, <u>oil droplets rising under an ice sheet would quickly collect in a pool without forming mousse</u>.

These conclusions should be tempered somewhat by some later tests that Science Applications, Inc. performed with Prudhoe Bay crude exposed in cold weather in a wave tank in Alaska (30). In these tests energy was added continuously to the oil on water using a wave maker. During the first 24 hours no emulsification was observed, but as the oil/water interfacial surface tension dropped, a significant amount of water was taken up in the oil. Significant emulsification did not occur until some of the more volatile and less viscous components had been removed by evaporation and dissolution processes. The test investigators suspected that the emulsion stabilization process may have been enhanced by incorporation of organic rich suspended particulate material and even by microbial or photochemical oxidation. It therefore seems clear that although mousse is not <u>likely</u> to form in an arctic spill, it could form if the oil is left to weather in high energy areas for long periods of time.

Emulsions of Prudhoe Bay crude oil have been produced at the Coast Guard R & D Center (6). These emulsions had a density of 0.98 g/cc, which indicates that they might either move between ice pieces on the surface or even under them, since a typical ice density is about 0.91 g/cc.

Oil-in-water emulsion could present a difficult spill response problem in the Arctic. As it weathers, the mousse is likely to become quite dense, so that it might sink, float partly suspended under the water, move between pieces of ice, or even move under pieces of ice. The positive consideration is that it is very unlikely to form unless the oil is permitted to remain on water for long periods of time in a relatively high energy environment.

2.9 <u>Biodegradation</u>

Microbial degradation is an important process in weathering and the eventual disappearance of oil spilled in an aquatic environment (31). Bacteria, yeasts, and molds attack the hydrocarbons, transforming them into more soluble compounds that are again broken down by microorganisms until the final product is carbon dioxide and water.

Biodegradation is more complex than either physical or chemical degradation. The process cannot be attributed to a single type of micro-organism, but rather is caused by microbiological communities. In addition, the ability of microorganisms to degrade petroleum appears to be an adaptive process; that is, organisms from an area where petroleum is present will degrade oil more rapidly than organisms from areas that are normally free of petroleum products. In addition, bacteria are substrate-specific (32). This means that bacteria are highly specialized and only a limited number of hydrocarbons can be used by any one special bacterial strain. Also, even if the proper bacteria are present, the extent to which degradation will occur is governed by the oxygen, nitrogen, and phosphate salt content of the environment. The application of these nutrient fertilizers, either on land or in an aquatic environment, causes a substantial increase in degradation of oil. As the oil is degraded in the Arctic, the supply of nutrients such as nitrogen and phosphorus are rapidly depleted by the biological activity and therefore fertilization is required to maintain rapid rates of degradation. Bacterial seeding of spills may also stimulate degradation, but this procedure has

not been documented in the Arctic.

Temperature also influences oil degradation. At low temperatures, the low-boiling fractions take longer to evaporate and the activity of the bacteria is slowed down. Nevertheless, it has been demonstrated that even for low temperatures characteristic of the aquatic environment of Alaska, oil-degrading activity of micro-organisms still exists.

Biodegradation continues at low temperatures, but at a lower rate. The species capable of oxidizing oil at near 0°C do so only at 5 to 10% of the rate of oxidation by species active at 25°C. The rate of degradation is also affected by the bacteria that feed on the bacteria that feed on the oil. When these increase in numbers, the degradation of the oil slows or stops (32).

Although many species of micro-organisms are capable of biodegrading petroleum products, psychrophilic pseudomonads are generally the dominant species in the marine environment. These organisms have been observed to degrade petroleum in the Arctic at temperatures as low as 1.1°C. Although most micro-organisms have their best growth at temperatures of 15 to 20°C, psychrophilic bacteria have been routinely observed to grow at temperatures of -2.5°C, and have even been observed to grow at temperatures of -5.5°C (31). This ability to grow at low temperatures makes the psychrophilic bacteria the dominant strain for the biodegradation of petroleum in the Arctic.

Biodegradation rates for petroleum in the sea are usually limited by the numbers of micro-organisms available, scarcity of essential nutrients, and low temperatures (33). Low concentrations of nitrogen and phosphorus in sea water have been shown to prevent extensive petroleum biodegradation.

Atlas performed biodegradation tests at Prudhoe Bay in 1973 that showed that until 15 July the bay was highly stratified, with a bottom layer of cold, saline, nutrient-rich water covered by a layer of warmer, almost fresh, nutrient deficient water (33). In the spill tests, bacteria populations increased under surface slicks, with the largest increase under the fertilized slicks, showing that fertilization enhanced biodegradation.

Over all, the tests showed that there was an adequate oil degrading microbial population that could extensively degrade Prudhoe Bay crude in Alaskan waters. Seeding with effective psychrophilic oil degrading micro-organisms might enhance the rate of degradation (33).

Atlas conducted more tests during the summers of 1975 and 1976. This time an open flow-through test system was set up using the sea water collected a few meters offshore in the Chukchi Sea at Point Barrow, Alaska (34). The system was used to determine the extent of microbial degradation of Prudhoe Bay crude. After 51 days of exposure during the summer of 1975, the weight loss caused by microbial degradation was 10% for the oil treated with water-soluble fertilizer and 17% for the oil treated with oleophilic (oil absorbing) fertilizer.

In the same tests Atlas also investigated biodegradation under ice (34). To perform these tests, crude oil was released under ice near Barrow and observed by divers. During 21 days of exposure, the oil under ice lost 9% of its weight, which it is assumed reflects the restricted evaporative losses for oil trapped under ice. This led to the conclusion that the losses caused by biodegradation were not significant.

The oil under ice tests showed

that little change in oil accumulation will occur under ice cover in winter. Only a small number of hydrocarbon degrading microorganisms occur in sea ice, which limits the rate of biodegradation of oil on or under ice.

In another paper summarizing the results of their tests over several seasons, Horowitz and Atlas concluded that biodegradation may vary significantly from year to year (35). The population of oil-degrading bacteria was high during the ice-dominated summer of 1975, which suggests that ice may affect population levels. (35). Further, biodegradation may vary widely between different sites, even those located close together. This indicates that the degradation process may be site specific.

2.10 <u>Oxidation</u>

Chemical weathering involves atmospheric oxidation of oil on the surface of water, ice, or land (32). It could also be extended to include the chemical weathering of reduction reactions that may occur in low-oxygen water layers as the oil sinks.

Photo-oxidation is the most significant oxidation reaction. This is a spontaneous reaction of a compound with molecular oxygen at moderate temperatures. Since most photo-oxidations are accelerated by increasing temperatures as well as by light, one would expect that these processes are less significant in the overall weathering of oil in the Arctic as compared to more temperate zones. Most studies of oxidation have involved Middle East crudes. Since the oxidation process depends on the composition of the oil, these studies cannot be used to predict the oxidation characteristics of Prudhoe Bay crude (32).

WEATHERING REFERENCES

1. Mackay, Donald, Wan Ying Shiu, Khon Hossain, Warren Stiver, Diane McCurdy, and Sally Paterson, Development and Calibration of an Oil Spill Behavior Model, Report No. CG-D-27-83, U. S. Coast Guard Research and Development Center, Groton, Connecticut, September 1982.

2. Glaeser, J.L. LTJG and LCDR George P. Vance, A Study of the Behavior of Oil Spills in the Arctic, U.S. Coast Guard, Office of Research and Development, Report 714108/A/001,002, Washington, D.C., February 1971.

3. NORCOR Engineering and Research, Limited, The Interaction of Crude Oil With Arctic Sea Ice, Beaufort Sea Technical Report #27, Beaufort Sea Project, Department of the Environment, Victoria, B.C., December 1975.

4. Ramseier, R.O., G.S. Gantcheff, and K. Colby, Oil spill at Deception Bay, Hudson Strait, Environment Canada Scientific Series Report #29, Ottawa, Canada, 1973.

5. Deslauriers, P.C., S. Martin, B. Morson, and B. Baxter, The Physical and Chemical Behavior of the Bouchard #65 Oil Spill in the Ice Covered Waters of Buzzards Bay, a report prepared by Arctec, Inc. for OCSEAP, NOAA, June 1977.

6. Tebeau, P.A., T.M. Meehan and J.C. Myers, A Laboratory Experiment on Oil Weathering Under Arctic Conditions, U.S. Coast Guard Research and Development Center, Groton, Connecticut, August 1982.

7. Twardus, E.M. A Study to Evaluate the Combustibility and Other Physical and Chemical Properties of Aged Oils and Emulsions, a study prepared for Environment Canada, December, 1980.

8. Personal communication with Mr. Elwin Davis, Atlantic Richfield Company, Harvey Technical Center, Harvey, Illinois, February, 1984.

9. Personal communciation with the plant supervisor, Atlantic Richfield Cracking Plant, Prudhoe Bay, Alaska, April, 1984.

10. C-Core, An Oilspill in Pack Ice, a report of the KURDISTAN Spill, March 1979, compiled for Environment Canada by the Centre for Cold Ocean Resources Engineering, January 1980.

11. Peterson, Hanne K., Fate and Effect of Bunker C Oil Spilled by the USNS Potomac in Melville Bay, Greenland, 1977, Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills, Keystone, Colorado, June 1978.

12. McAuliffe, Clayton, Dispersal and Alteration of Oil Discharged on the Water Surface, Proceedings of the Symposium on the Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms, Seattle, Washington, 1976.

13. Lu, Benjamin C.Y. and Jiri Polak, A Study of the Solubility of Oil in Water, Environment Canada Report EPS-4-EC-76-1, March, 1973.

14. Minister of Transport, Report of the Task Force Operation Oil, (Clean up of the ARROW oil spill in Chedabucto Bay), 1970.

15. Cox, J.C., R.A. Shelsby, and L.A. Schultz, Oil Dispersants for Arctic Seas, Alaskan Beaufort Sea Oilspill Response Body, October 1980.

16. Schulze, Robert, P.C. Deslauriers, and L.A. Schultz, Oil Spill Response in the Nearshore Beaufort Sea, Alaska Oil and Gas Association, August, 1978.

17. Abdelnour, R., A.M. Nawwar, P.O. Hildebrand, and W.F. Purves, Novel Countermeasures for an Arctic Offshore Well Blowout, Report 194C-3, ARCTEC CANADA, LTD., submitted to Research and Development Division, Environment Canada, Ottawa, Ontario, March, 1977.

18. Topham, D.R.,Hydrodynamics of a Blowout, Beaufort Sea Technical Report #33, Department of the Environment, Victoria, B.C. December 1975.

19. McMinn, T.J. LTJG USCG, Oil Spill Behavior in a Winter Arctic Environment, Offshore Technology Conference, Houston, Texas, 29 April - 2 May 1973.

20. Buist, I.A., W.M. Pistruzak, and D.F. Dickins, Dome Petroleum's Oil and Gas Undersea Ice Study, SPILL TECHNOLOGY NEWSLETTER, May-June 1981.

21. Buist, I.A., S.G. Potter, and D.F. Dickins, Fate and Behaviour of Water-in-Oil Emulsions in Ice, Proceedings of the Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1983.

22. Nelson, William G., and Alan A. Allen, The Physical Interaction and Cleanup of Crude Oil with Slush and Solid First Year Sea Ice, Proceedings of the Fifth Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1982.

23. Personal communication with Edward Tennyson, Department of the Interior, Minerals Management Service, concerning combustion tests performed at OHMSETT test facility, Edison, New Jersey, winter of 1983-1984.

24. Smith, N. K., In Situ Burning of Prudhoe Bay Crude in Broken Ice, a preliminary (unpublished) report of burning tests performed at the OHMSETT test tank, Edison, N. J., winter of 1984-1985.

25. Buist, Ian and E. M. Twardus, In Site Burning of Uncontained Oil Slicks, Proceedings of the Seventh Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1984.

26. Buhite, T.R., Cleanup of a Cold Weather Terrestrial Pipeline Spill, Proceedings of the 1979 Oil Spill Conference, Los Angeles, California.

27. Lewis, E.L. Oil In Sea Ice, Pacific Marine Science Report 76-12, Institute of Ocean Sciences, Sidney, B.C. 1976.

28. Thomas, D.R., Behavior of Oil Spills Under Sea Ice - Prudhoe Bay, Flow Research Report No. 175 appearing in the Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of Principal Investigators for the year ending March 1981, Volume VI: Transport.

29. Galt, J.A., Investigations of Physical Processes, AMOCO CADIZ Oil Spill, NOAA/EPA Special Report, April 1978.

30. Payne, James R., Bruce E.Kirstein, G. Daniel McNabb,Jr., James L. Lambach, Celso de Oliveira, Randolph E. Jordan, and Wilson Hom, Multivariate Analysis of Petroleum Hydrocarbon Weathering in the Subarctic Marine Environment, Proceedings of the 1983 Oil Spill Conference March, San Antonio, Texas, 1983.

31. Karrick, Meva L, Alternatives in Petroleum Resulting from Physio-Chemical and Microbiological Factors, Ice: Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms, Volume I, edited by Donald C. Malins, Academic Press, Inc, New York, 1977.

32. Isakson, J.S., J.M. Storie, J. Vagners, G.A. Erickson, J.F. Kruger, and R.F. Corlett, Comparison of Ecological Impacts of Postulated Oil Spills at Selected Alaskan Locations, U.S. Coast Guard Report No CG-D-155-75, Washington, D.C. Office of Research and Development, June 1975.

33. Atlas, Ronald M., Fate and Effects of Oil Pollutants in Extremely Cold Marine Environments, Jet Propulsion Laboratory Report for the Office of Naval Research, November 1973.

34. Atlas, Ronald M., Fate and Effects of oil Pollutants in Extremely Cold Marine Environments, Office of Naval Research, Contract no. N00014-76-C-0400, December 1976.

35. Horowitz, A. and R.M. Atlas, Oil Biodegradation in Arctic Coastal Waters, Proceedings of the Twenty-Seventh Alaska Science Conference, Fairbanks, Alaska, August 1976.

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3.0 ARCTIC OIL SPILL BEHAVIOR

Spill behavior in the Arctic is mostly concerned with ice condtions; however, even though a spill may occur in ice, spill movement is likely to be delayed until break-up. As a result, spill movement on open water is an important consideration for all arctic spills.

3.1 Oil Spreading on Open Water

Oil spreading on open water is the normal or "baseline" condition even though the open water season in the Arctic is very short. All other conditions of spreading, such as oil in ice, oil on ice, and so forth, are variations of the open water spreading concept.

There are several phases to consider in the physics of open water spreading: inertia spreading, viscous spreading, and surface tension spreading (1). In the Arctic the surface tension phase of spreading is absent. This means that the motion ceases when the oil reaches a certain thickness, usually about 5 mm (2).

The Fay-Hoult model for spreading shows that gravity is important as spreading begins because of the hydrostatic pressure of the thickness of the oil slick (3). At first the spreading is retarded primarily by inertia. Later gravity-induced spreading is retarded by viscosity (shear stress) at the oil-water interface. In warm water conditions, the gravity effects are finally diminished as the slick thickness decreases, and surface tension forces drive the spreading until balanced by the viscous forces. Field experiments in the Arctic, however, have shown that the spreading does not enter the surface tension viscous phase in cold weather (4).

The initial phase of spreading is caused by the thickness of the spill at the source and the physical properties of the oil. The next phase of spreading is caused by currents and wind.

In the absence of wind, spilled oil can be expected to move with the current at the current velocity. If wind is present, the spill movement will also have a component parallel to the direction of the wind at 3% of the wind speed. Thus if both current and wind are present, spill drift will be the vector sum of the current velocity and 3% of the wind velocity. The direction and speed of movement of the spill can be determined using standard maneuvering board vector addition. The vector addition is demonstrated in Section 5.

Spills do not usually continue to spread out in uniform, continuous sheets. Generally the spilled products are soon broken up by winds and waves.

In high winds, oil slicks have often been observed to break up in patterns of long, thin streaks (5). These streaks are generally called windrows since they are oriented very near parallel to the wind direction. Although the dynamics of windrow formation are not well understood, the conditions under which they are formed have been observed. For example, during the Santa Barbara spill, that began on 28 January 1969, it was observed that the oil remained in patches until a steady wind of about 8 knots herded the oil into extended bands parallel to the wind. It appears that 8 knots is about the minimum velocity at which windrows will form.

The windrows of oil have also been observed to rapidly realign with changing wind direction (5). The streaks are generally long and may be spaced from a few centimeters to 300 meters apart on the open ocean.

Waves also have an important effect on the behavior of open water spills. Breaking waves are the dominant agent breaking up a continuous slick on open water (6). These waves cause the dispersion of oil in the form of submerged droplets. As the oil slick is torn by the intense turbulence of breaking waves, air is entrained. The mixing of oil, water, and air could produce an oil-in-water emulsion in addition to oil droplets.

The motion of oil droplets in water is determined by the turbulent flow in the water. The turbulence is generated by winds, currents, and breaking waves. In breaking waves, the oil particles that are less dense than water tend to rise, the large ones rising faster than the smaller ones. If the rising particles encounter a slick on the surface, they coalesce with the slick. Droplets that are driven deeper into the water may be carried away by currents. Some oil particles may even be incorporated into sediments and some may dissolve, but this process is very slow (6).

The effect of the waves is also determined by the thickness of the slick. Thick slicks are not generally affected by the waves. In fact, thick slicks dampen most small waves and reduce the tendency of breaking for larger waves. When the slick is thin, it may be broken up into smaller slicks by breaking waves. As the spill continues to weather, the oil may also form lumps and small particles.

In a similar way, the thickness of the slick is important in determining the amount of oil that is dispersed into the water. In laboratory tests of oil dispersion by breaking waves, Milgram found that increasing slick thickness from 0.5 mm to 5.5 mm reduces dispersion by 96% (6). Viscosity is also important in dispersion. Low viscosity oil is more easily dispersed than high viscosity oil. Since aging increases viscosity, weathering decreases the amount of oil dispersed by waves.

The properties model was used to compute typical open water spill spreading situations in arctic environmental conditions (7). Several spill sizes were investigated using the typical temperature of arctic water of 0°C and an average wind speed of 14 knots.

Figure 3.1.1 shows the predicted spill radius for an instantaneous release of 50,000 barrels of oil. The curves show that surface spreading occurs very quickly, and that at the end of the first hour the thick portion of the slick has almost reached its maximum radius. Based on this model, the central portion of the spill would be 2.8 cm thick. This heavy portion of the spill would be feeding a thin slick (about 5 microns) that would grow from a radius of about 800 m out to a radius of more than 10,000 meters. The thick inner slick would continue to expand somewhat until about the third day after the spill, when it would begin to decrease in size as more of its volume is drawn away by the expanding thin slick.

The reader may wonder why the spreading model shows that the central portion of a 50,000 barrel spill would be 2.8 cm thick whereas field tests show that Prudhoe Bay crude released on cold water reaches a terminal thickness of about 5 mm (4). Probably the best answer is that the model predicts what would happen in a large, almost instantaneous spill, and the field tests report what happened when 50 to 100 gallons of oil were released under carefully controlled conditions. In an actual high-volume under sea blowout situation, oil may accumulate on the surface (just above the source of the spill) to a thickness of tens of centimeters

before it can spread out. If, in the Arctic, the thick part of the slick cools to its pour point before the oil can spread to its normal terminal thickness, then the resulting slick is likely to be more than 5 mm thick.

This line of reasoning can be substantiated by what is already known about the physical properties of Prudhoe Bay crude as it weathers. Figure 2.2.1 shows that crude spilled at 0°C becomes more viscous and approaches a semi-solid state within hours of release and in every case it is semi-solid after the first day. Further, Figure 2.3.1 shows that the pour point increases rapidly to +5°C in the first day. Based on this information, one has evidence to conclude that a spill on open water may have a thickness that ranges from 5 mm to several centimeters depending on how rapidly it cools. If the spill is continuous, a 50,000 bbl release 3 cm thick would have a radius of about 300 m, or a radius of about 700 m if it spreads to a terminal thickness of 5 mm. That is to say, the range of the radius of a continuous slick is likely to be 300 to 700 m.

Based on reports of large spills, however, the slick is not likely to remain continuous for a long period of time, even in a low energy wave environment. Instead, the spill is likely to stretch out in wind rows and break into pancakes 10 to 30 cm in diameter and 5 mm to several cm thick. It is very likely that the heavier parts of the spill would bleed off into a sheen a few microns thick as shown in Figure 3.1.1. As time goes on, the larger formations are likely to break up into globs a few centimeters in diameter down to particulates that are a few millimeters in diameter. These spill components would move with currents, winds, and waves to be deposited on shorelines, ice, or move out to sea, depending on the local situation. At this point spill behavior becomes a process of transport rather than spreading.

Figure 3.1.2 shows the predicted radius of a continuous 100,000 bbl spill. A continuous slick would have a radius of 400 m and a thickness of about 3.2 cm.

Figure 3.1.3 shows predicted spreading for a 20,000 gallon spill of arctic diesel. These curves differ from those representing Prudhoe Bay crude in two ways. First, the thicker part of the slick has a much larger radius than the thin slick. Second, spreading stops after 23 hours. A spill radius of 1,150 m shown on the curve would result in a slick thickness of about 0.02 mm.

Figure 3.1.4 shows predicted spreading for a 50,000 gallon spill of arctic diesel. In this case, spreading stops in 13 days. The slick would be about 0.03 mm thick for a spill radius of 1,350 m.

Figure 3.1.5 is provided as a fall back position to estimate spill size or slick thickness. Figure 3.1.5 simply takes spill volume and thickness and computes a radius of the area covered by a spill if it were circular and continuous. The radius is used because it is very difficult to measure, or even estimate, spill area in the field. Radius can be measured, or estimated, from a surface ship in the spill area or by flying over the slick. In any case, Figure 3.1.5 can be used in a number of ways. If spill volume is known and slick thickness can be measured, then the spill radius can be estimated from the curves. Or, if spill radius can be measured or estimated and slick thickness can be measured, then spill volume can be estimated. Also, if both spill volume and radius are known, slick thickness can be estimated.

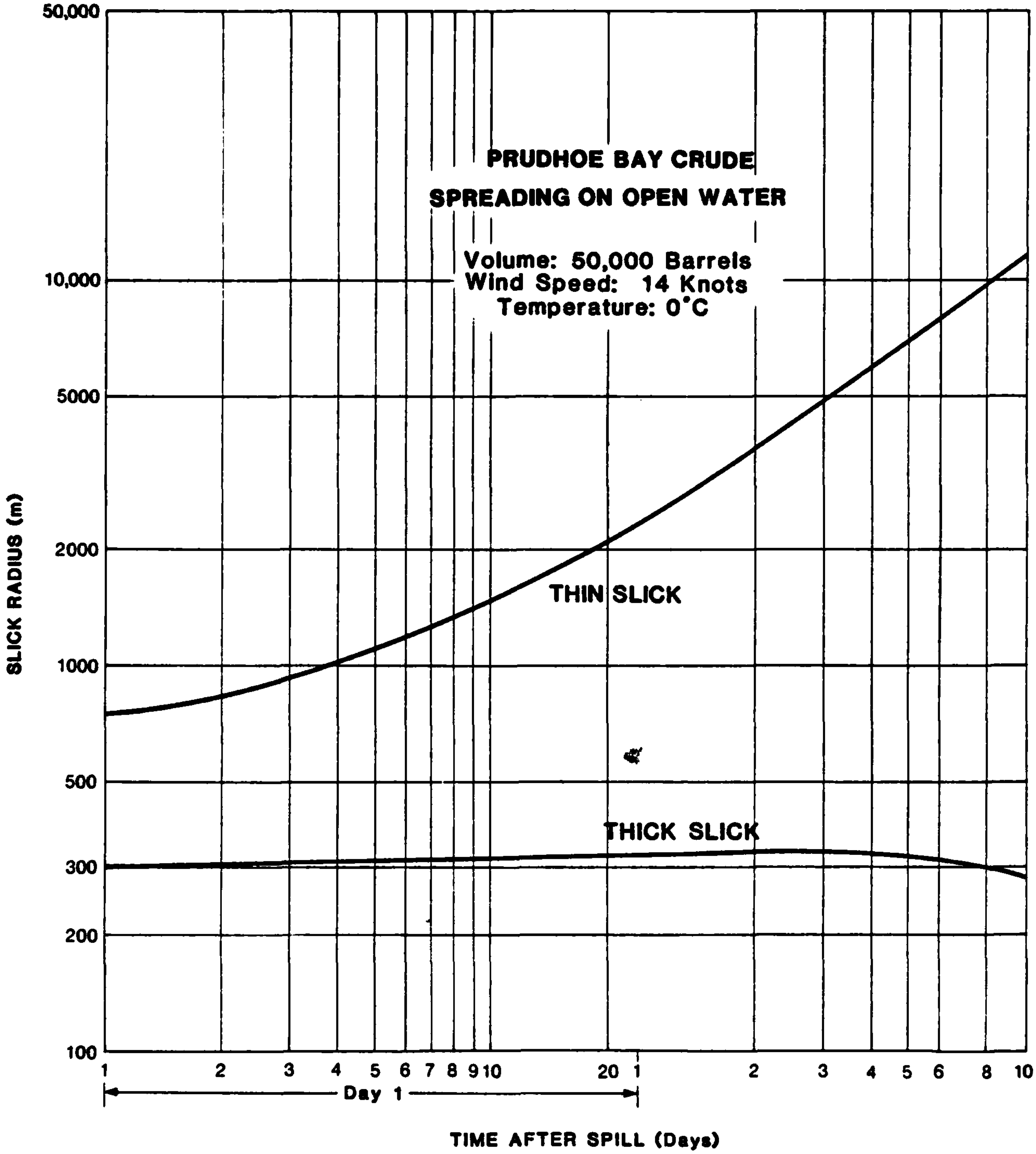

FIGURE 3.1.1 PRUDHOE BAY CRUDE OIL SPREADING ON OPEN WATER
Day 1 shows a scale in hours from the first hour after the spill until the end of day 1.

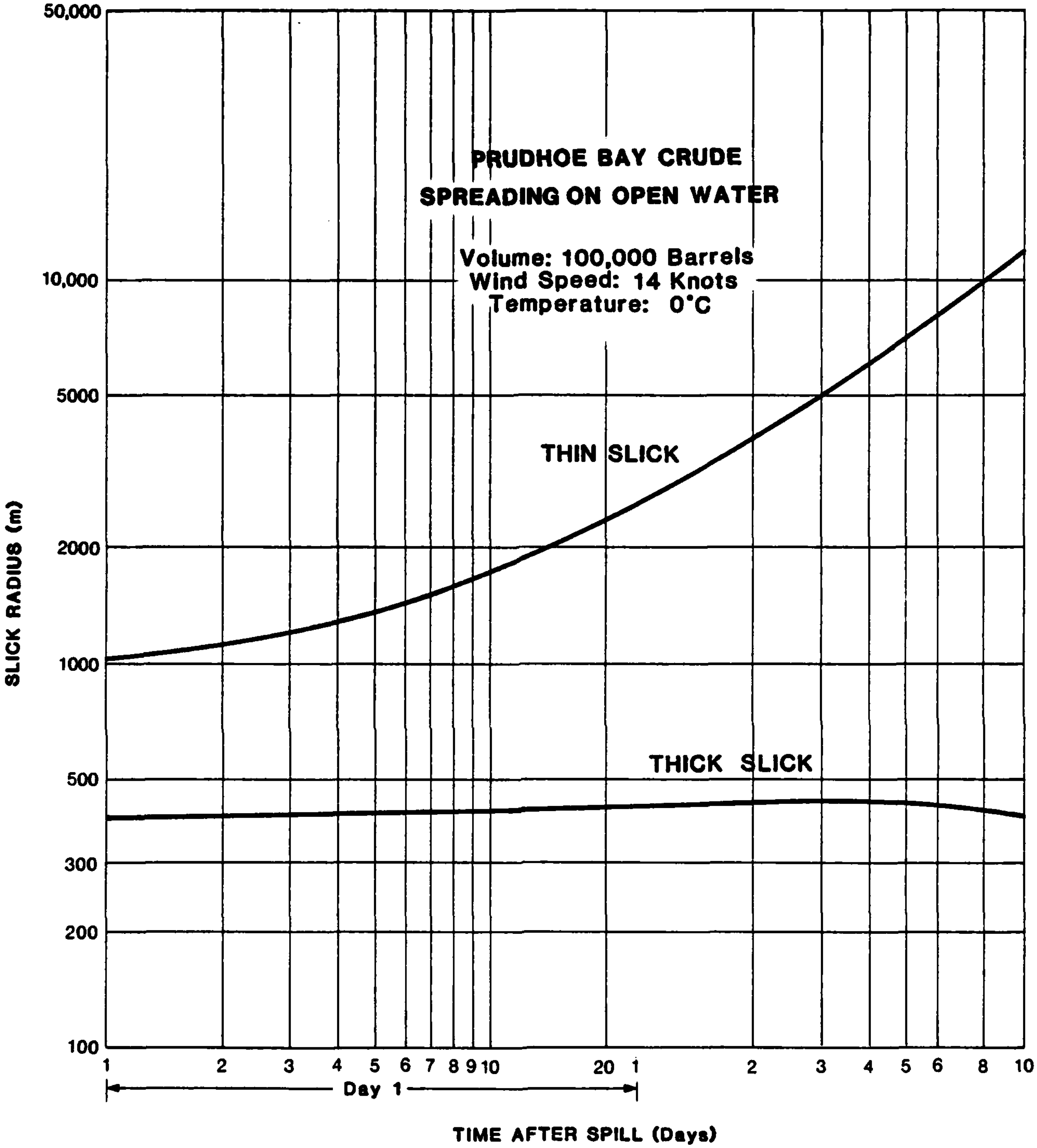

FIGURE 3.1.2 PRUDHOE BAY CRUDE OIL SPREADING ON OPEN WATER
Day 1 shows a scale in hours from the first hour after the spill until the end of day 1.

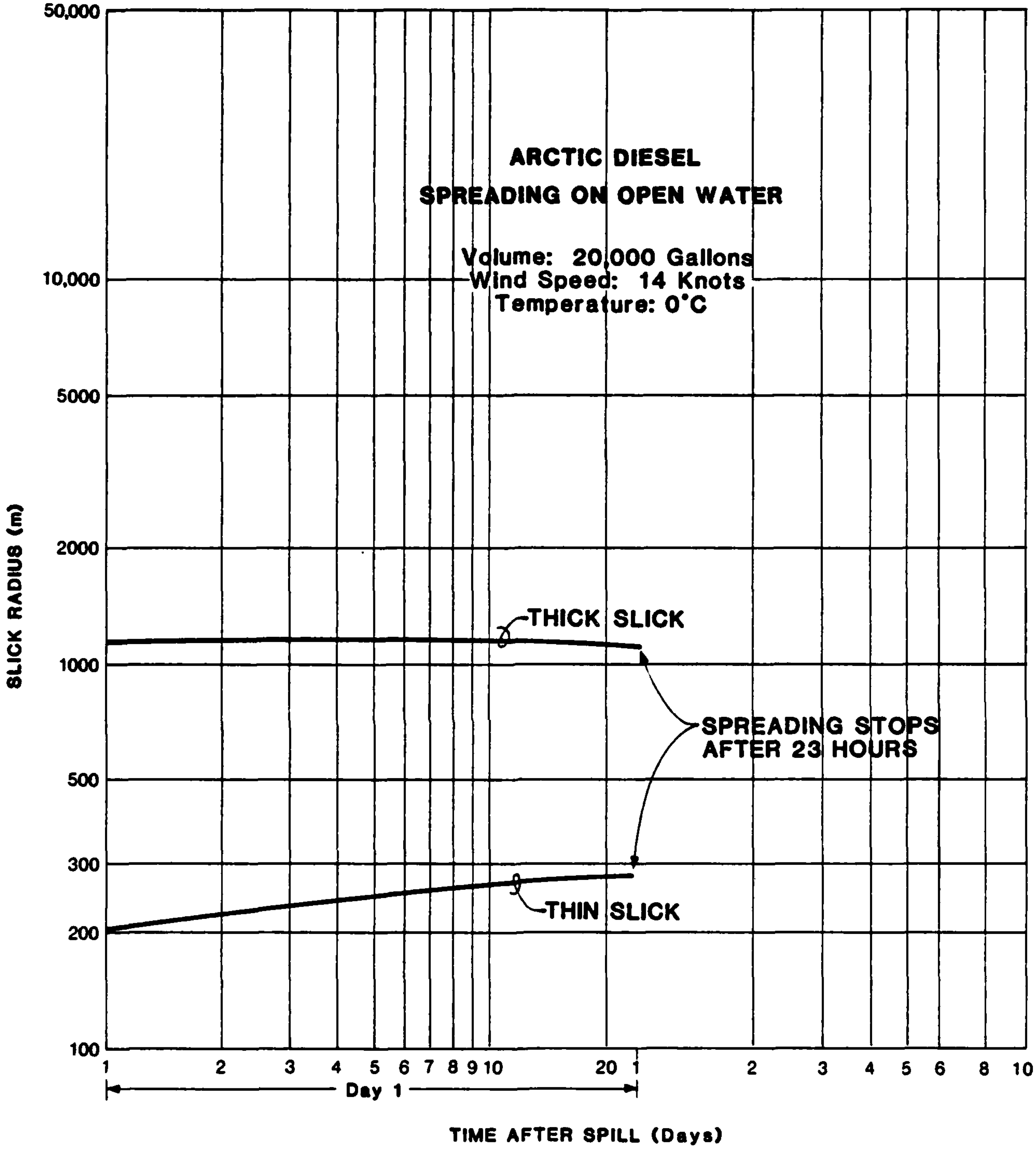

FIGURE 3.1.3 ARCTIC DIESEL SPREADING ON OPEN WATER
Day 1 shows a scale in hours from the first hour after the spill until the end of day 1.

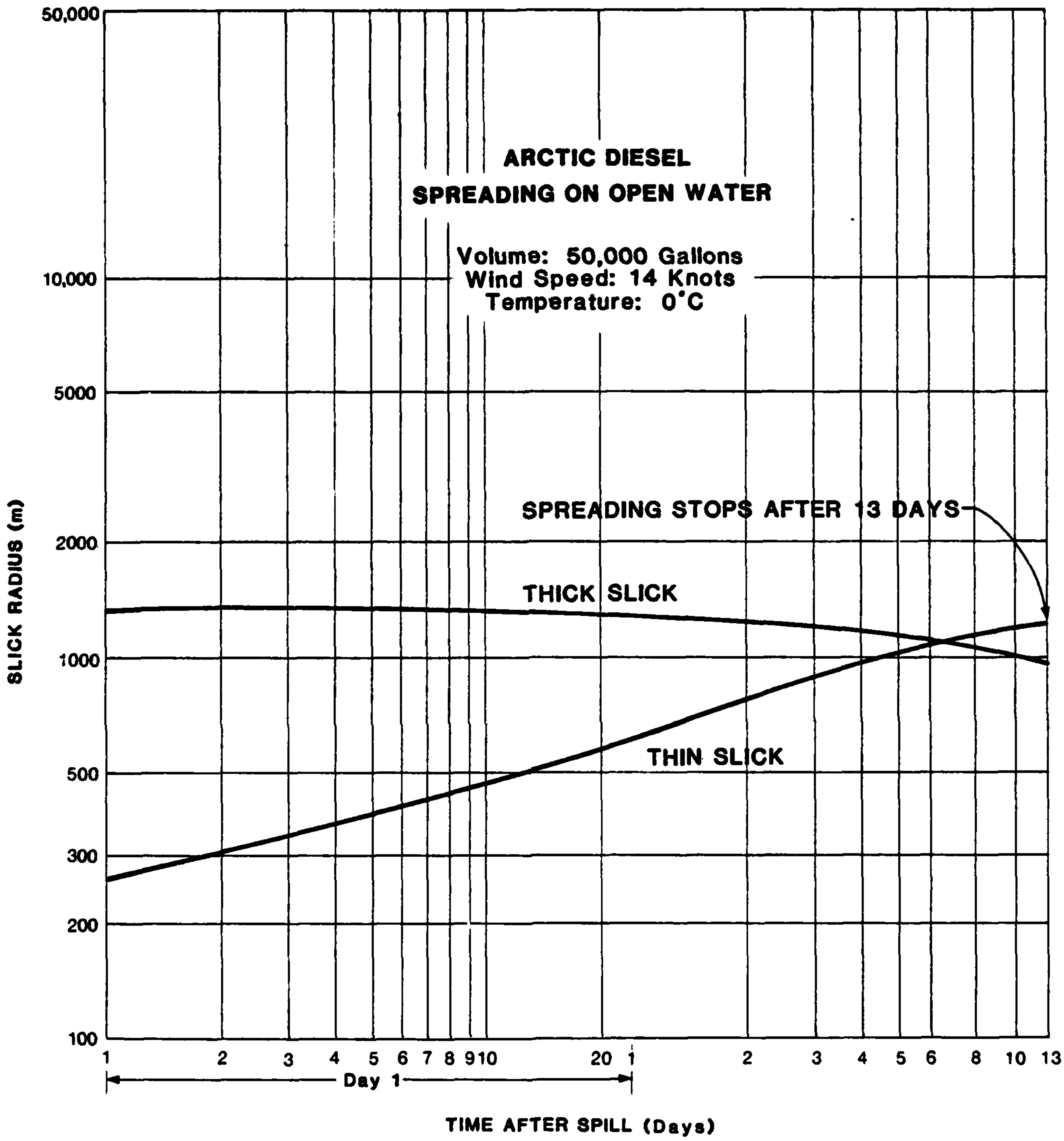

FIGURE 3.1.4 ARCTIC DIESEL SPREADING ON OPEN WATER
Day 1 shows a scale in hours from the first hour after the spill until the end of day 1.

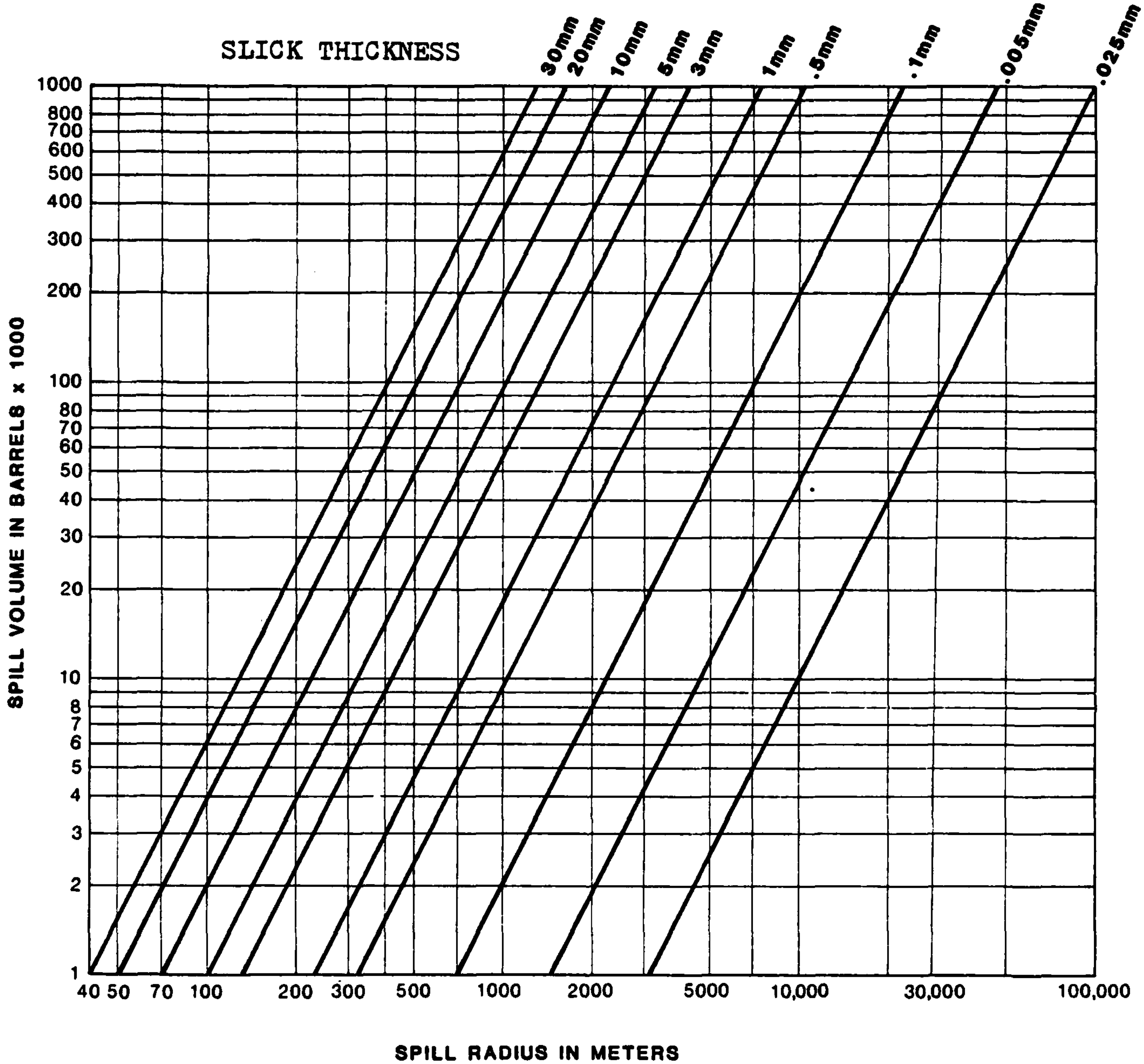

FIGURE 3.1.5 SPILL RADIUS ACCORDING TO VOLUME SPILLED AND SLICK THICKNESS

3.2 Sedimentation of Oil

In most cases, oil has a density that is less than water and floats. In a few extreme cases, a weathered heavy product such as #6 fuel oil or a highly weathered crude may have a density that increases to the point that the oil sinks. Although this does not happen often, it may sometimes occur and result in the loss of recoverable oil.

The density of oil may also increase when it becomes attached to heavier materials. For example, in a nearshore environment oil may coat heavier particulate matter and sink. This behavior pattern is generally called sedimentation of oil (3).

The increase in density during the sedimentation process can be the result of uptake by the oil of either organic or inorganic particulate matter. The nature of oil sedimentation depends on the physical characteristics of the oil and the properties of the sediments. Beach sediments are well-sorted with both high porosity and high permeability types; low tide sediments are water-filled and high tide sediments have air-filled voids. During a rising tide the wave action concentrates oily material near the high tide line regardless of the form of the oil. As the tide recedes, the stranded oil is warmed by the sun, becomes less viscous, and penetrates the air-filled voids of sediments along the high tide line. Wave action reworking the beach during following tidal cycles coats the sandy particles. The void-filling may restrict direct penetration of oil carried upon the next tide if the particles are small, or enhance the reworking of the oil if particles are large. The ultimate fate of oil particles in a beach depends on biological action, the history of sediment transport, and the nature of the hydraulic action that moves water through the sediments.

Sediments in low energy areas are typically fine grained and high in organic content (3). They have high porosity, but as an aggregate, low permeability. Areas contaminated by oil are not likely to have extensive reworking if they lack both daily tidal cycles and seasonal cycles of erosion and deposition. Further, the high rates of sedimentation in low energy areas will rapidly bury the oil. As a result, oil that has been stranded in typical low energy areas, such as salt marshes and tidal flats, is likely to remain in place for a long time.

Sedimentation may begin to occur soon after a spill incident. Oil will begin to adhere to organic material such as clay, silt, sand, or even shell fragments (8). More oil can be absorbed by smaller grained sediments than larger sediments. On a unit-mass basis, the smaller the grains are, the more total surface area there is. As a result, fine-grained clay minerals can remove large volumes of oil from the water and permit it to settle to the bottom.

There are a number of factors that increase the tendency of a spilled product to be combined with sediments.

- o <u>Size of spill</u> - as more oil is available, there is a greater chance the spilled products will combine with sediments
- o <u>Weathering</u> - as the weathering progresses, the density of the spilled products may increase to the point that they sink
- o <u>Amount of sediment</u> - sedimentation is more likely to occur when more sediment is available
- o <u>Water depth</u> - more sediments are generally available in shallow water

o Particle size - fine-grained materials have a greater capacity to hold oil.

Clay minerals absorb the greatest quantity of dissolved hydrocarbons, and the process is enhanced if organic matter is present (8). In a 1974 spill in the Gulf of Mexico, about 10% of the spilled oil became part of the upper 1.5 cm of the bottom sediments within about 5 miles of the spill. The water was 12 m deep and contained high levels of sediments from top to bottom. In another Gulf spill of 62,900 barrels of oil in 1970, only 1% of the oil found its way into the sediments and within a year nearly all of it had degraded. These observations seem to indicate that the kinds of sediments that mix with the oil affect the extent of sedimentation.

In some areas, however, spilled products have penetrated sediments to great depths and have remained in place for long periods of time (9). In a spill of #2 fuel oil in the salt marsh at West Falmouth, Massachusetts, in September of 1969, oil deposits reached their peak concentration 70 cm below the surface and small amounts were present down to 120 cm. Visits to the area showed that the spilled product had not degraded appreciably over a period of several years.

Spilled oil can combine with sediments and be transported in the water column in a number of different ways. Figure 3.2.1 shows some of the ways in which this might occur (10). The (A) section of the figure shows how oil may combine with sediments and circulate to the bottom. The figure shows the oil and particulates moving to the bottom; however, one might also postulate that storms or changing circulation patterns could also lift the products back to the surface.

Figure 3.2.1 (B) shows how weathering may cause a product to sink. In the case of the spill of a heavy oil, sinking as a result of increased density caused by weathering can occur quickly (11). The sinking of weathered Bunker C off Greenland described previously illustrates the point.

Figure 3.2.1 (C) shows what may occur as oil combines with sediments in a near shore environemnt. The oil is likely to become attached to sediments as it approaches the surf line where sediments are well mixed in the column of water. Additional sedimentation will occur at the shoreline, then the oil-coated sediments may be carried down the slope of the beach and be deposited beyond the surf zone.

In the spill of Bunker C from the ARROW at Chedabucto Bay, Nova Scotia, the surf action on the beaches and the wave action offshore broke the spilled oil up into small particles (12). In some places these particles were stirred in the water to a depth of at least 80 m. Particles were 5 microns to 1 mm in diameter with some as large as 2 mm. The concentration of particles decreased with depth since they retained their buoyancy. Particles were tracked from Chedabucto Bay southwest along the Nova Scotia coast for a distance of 250 kilometers in a band extending up to 25 kilometers offshore. The front of the band advanced at a rate of about 8 km/day. Two weeks after the wreck, particles were found in a tongue 10 km wide exending 70 km into the ocean. A week later they disappeared after having been blown toward Sable Island.

3.3 Oil Spreading in Broken Ice

Oil moving in broken ice can be expected to enter the cracks and leads between the various floes and chunks of ice. The oil will then

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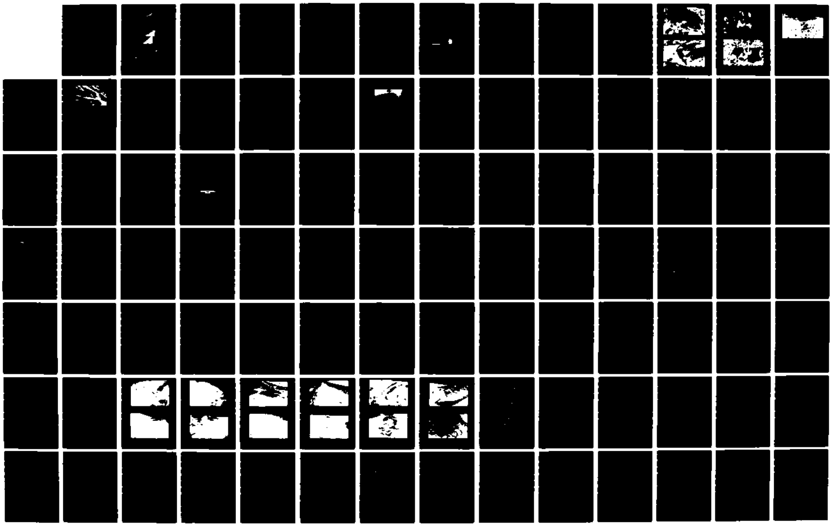

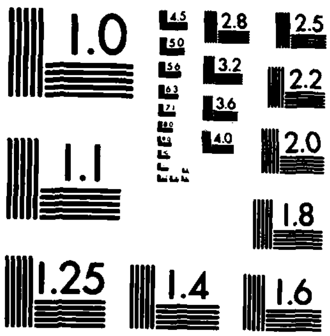
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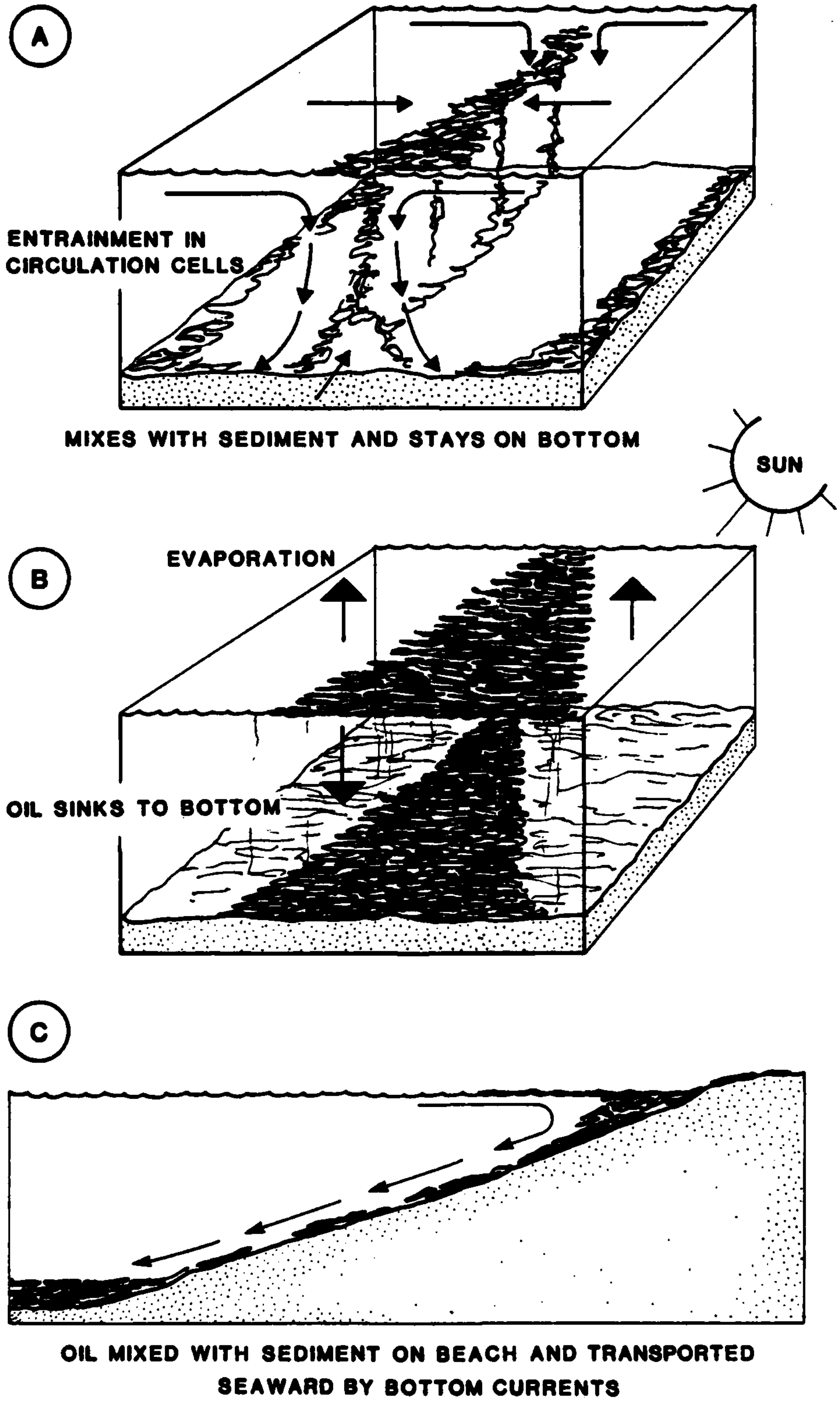

FIGURE 3.2.1 SEDIMENTATION OF OIL [10]

spread to some equilibrium thickness governed by ice concentration and the physical properties of the oil (13). At first the ice will restrict the flow of the oil so that the area covered by the spill will be less than for open water. As break-up progresses, or as the oil enters an open area, the floes and pieces of ice will move freely with winds and currents. At this point the effect of the ice becomes uncertain. Instead of restraining the movement of the oil, the ice may now transport the oil great distances from the original spill and contaminate a wider area than if the ice had not been there at all.

Describing the behavior of oil spreading in broken ice is a formidable task. There are two parts to the spreading problem; (1) oil spreading between ice pieces as a result of the hydrostatic pressure of the thickness of the oil, and 2) oil movement in the ice under the influence of wind, waves, and currents.

The way that oil moves through broken ice has not yet been described with any degree of precision; however, several studies tracing oil movement in ice provide insights into how oil would move in an ice field in a real spill situation. These studies will be reviewed to determine how the results can be applied to an actual spill. In addition, there are a few reports of actual spills that occurred in broken ice. These reports will also be reviewed to provide some information about how the oil can be expected to move.

3.3.1 Spreading Against Broken Ice

In 1981 ARCTEC, Incorporated performed a series of tests for the Coast Guard Research and Development Center to determine the behavior of oil spilled in or near a field of broken ice (14). The tests were performed in a 14 m long insulated, glass-walled ice flume. The working depth of water was 40 cm and the ice pieces were 8.25 cm square for some of the tests and 16.5 cm square for others. Although the ice flume is a substantial piece of test equipment, the system did impose some test artificialities in that only one dimensional flow could be tested and the size of the ice pieces was limited. In spite of these limitations, the tests developed a great deal of valuable information.

The flume tests showed that a field of broken ice with a concentration of less than 25% can provide some degree of containment for a spill that is spreading on water. The tests showed that spreading oil herds the ice along the surface of the water. If the ice movement is restrained at some point, the ice concentration increases to the extent that the oil is contained. The tests found that the ice provided total containment for the heavier oils. Based on these tests, fresh Prudhoe Bay crude would be virtually contained by the ice with some small quantity seeping through. After the crude had weathered for about a day, it would be completely contained by the ice. Diesel fuel would not be contained by the ice and could be expected to move through the field at nearly the open water rate.

One of the important observations made during the tests concerns the way that spilled oil tends to herd an unrestrained field of broken ice and to concentrate a restrained field of ice. (A restrained ice field is one in which the ice is floating freely but it is ultimately restricted from moving when a force is exerted on it.)

Spilled oil exerts a horizontal hydrostatic force. Since the oil floats over the water, its surface is higher than the water surface. This unbalanced hydrostatic force

therefore pushed the ice blocks in the direction of spreading. As a result of this action, the horizontal hydrostatic force of the oil in the test flume kept the ice field packed to its maximum concentration. During tests in restrained ice fields, initial ice concentrations of 23% increased to 80 or 90% as soon as the oil was released. As a result, restrained ice almost always provided total containment for heavy oil regardless of the initial concentration of the ice. The light diesel fuel was virtually contained with some leakage in a highly concentrated ice field.

The fact that oil can herd ice in an unrestrained field and can be contained by a restrained ice field has an important application for oil spill response personnel in the field. In spring most ice fields have some large floes mixed in areas of broken, rotting or deteriorating ice. A large spill in this kind of an ice environment could be expected to herd the fields of broken ice, but in a short distance this ice is likely to be restrained by a large floe. Because the floe is not fixed in space does not mean that it would not provide the necessary restraint. Its mass is such that it may not be easily moved by the oil, and its overall drift may be so slight that in terms of the spill movement in the immediate area, it would be an effective barrier.

<u>Because of the interaction of broken ice and large floes, the OSC is likely to see spilled oil sweeping light accumulations of ice out of the area until the broken ice becomes restrained by a large floe. At this point the concentration of the broken ice is likely to increase to the point that it would contain a spill of relatively heavy oil and keep it from spreading farther.</u>

Ice herding could not be expected, of course, for thin slicks moving against heavy fields of broken ice. Because of its internal friction and inertia, the unrestrained pack resists the horizontal movement of the spilled oil. The effective moving force depends on the density and the thickness of the oil plus the weight and draft of the ice blocks. For the tests in the ice flume, the oil had to be 1 to 2 cm thick to overcome the resistance of the ice.

Thin slicks of relatively heavy oil moving into densely packed ice fields will be restrained by the ice because the vertical dimension of the slick does not provide enough hydrostatic pressure to permit movement between gaps in the ice. The reduction in hydrostatic pressure also provides the means of restricting the movement of a thick slick in ice. As the slick spreads, its thickness is reduced until finally it becomes so thin that it no longer has the hydrostatic head to move between the pieces of ice. At this point its movement through the ice stops and it is contained.

Depending on its thickness, an oil slick can exert a vertical or a horizontal hydrostatic force on a broken ice field. Oil that is less dense than both water and ice can ride over the ice and push it down in the water. Having done this, the oil flows freely over the ice at an open water spreading rate as if the ice were not there.

As mentioned earlier, the oil can also exert a vertical force on the ice if the thickness of the oil is either greater than or equal to the thickness of the ice. When this happens, the oil spreads over the ice field. It is important to remember that this kind of spreading is only likely to occur in light accumulations of newly forming ice.

The movement of the oil over the ice can be explained in two ways.

First, if the slick is thick enough, the weight of the oil pushes the ice down in the water. Second, if a spilled product, such as diesel, is much less dense than water, the buoyancy of the ice is reduced in the new medium and the ice sinks in the oil. In any case, the oil becomes free to move over the surface of the ice and begins to spread at a considerably faster open water rate. As the oil thickness decreases as a result of spreading, the ice blocks begin to resurface and the slick spreading is reduced to a slower rate characteristic of movement in an ice field.

The flume tests showed that light diesel fuel can be expected to flow easily through the gaps in a broken ice field. This is in contrast to the heavier oils, such as slightly weathered Prudhoe Bay crude, which would almost always be contained by the ice. The rate at which the diesel fuel seeps through the ice is a function of the thickness of the oil slick, the size of the ice blocks, and the concentration of the ice pack. It was also found that the velocity of the oil spreading through the ice is not increased by water velocity. The seepage rate of oil through the ice with no current was the same as when there was a high current. It appears that the ice insulates a thin oil layer from the effects of the current. Oil and ice movement are also affected by winds, but since this effect is much smaller, it was not considered in the tests.

Although it has been pointed out that a restrained ice field contains a spill of heavy oil, an unrestrained ice field does not provide this barrier because the oil pushes the ice pack downstream. In this case the oil slick then spreads out behind the ice.

3.3.2 Spreading in Broken Ice

Laboratory tests performed at the Coast Guard Research and Development Center were just slightly different from the tests performed in the flume, in that oil for the tests was added at the center of a static test basin and permitted to spread (13). In the flume tests oil was applied to open water and permitted to spread out to contact the ice either with or without an associated water current. This was essentially a <u>flow</u> situation rather than oil simply spreading in an ice field. Thus this report makes a slight distinction between oil spreading <u>against</u> broken ice in Section 3.3.1 and oil spreading <u>in</u> broken ice in this section.

In the Coast Guard tests, spreading of #2 home heating fuel (with properties similar to diesel) was basically independent of ice concentration in the range of 69 to 81%. The final slick thickness in these conditions was about 2 mm.

For Prudhoe Bay crude oil, spreading was about the same as for open water up to concentrations of 70%. For ice concentrations of about 80% and greater, spreading was reduced by the ice. The final slick thickness for the higher concentrations was about 11 mm.

For heavier oils, it was found that ice concentrations of 70% and greater are important in restraining spill movement and in increasing the slick thickness. The ice concentration does not affect light oils like #2 fuel oil or diesel because they move freely whether ice is present or not. Ice concentrations of less than 70% did not seem to have much effect on restricting spill movement or increasing its thickness for any of the test oils.

The Coast Guard tests also showed that heavy oils spread out unevenly

on open water or in an ice field. In a release of Prudhoe Bay crude in cold water, the oil tended to "stack up" in the center of the basin and successively thinner portions of the slick were arranged concentrically around the main oil mass.

This behavior is in agreement with the behavior of crude in an ice test basin (15). In tests performed for the Coast Guard by Arctec in 1975, crude oil was added in several installments in the center of a broken ice field. As more oil was added, the new oil had a tendency to spread out over the top of the old oil. The new oil, rather than spreading, tended to submerge some of the old oil and the ice. The area covered after 12 gallons had been added was not much greater than after 3 gallons had been applied. The oil seemed to be increasing in thickness rather than spreading. Later a single 12 gallon increment was added. The result was that some of the ice was submerged and some of the ice was moved away from the original position. The report of these tests concluded that the equilibrium thickness of crude spilled in broken ice cover could be highly variable, and most likely a function of the oil properties, the environmental conditions, the concentration of the broken ice, and the size and distribution of the ice pieces.

3.3.3 <u>Spreading in Grease Ice and Pancake</u>

Martin and others performed a laboratory experiment at the University of Washington in 1976 to determine the behavior of Prudhoe Bay crude oil and diesel in grease ice and in pancake ice (16). These two ice types are considered together because they occur together. The experiments were performed in a cold room basin that was 2.2 m long, 0.93 m wide, and 0.6 m deep.

Grease ice was grown in sea water in the chilled basin. A wave pattern was maintained in the basin so that the grease ice grew into pancake ice. The grease ice formed and remained a fluid, porous mass, finally achieving a thickness of 12 cm. This ice mass behaved like a buoyant, viscous fluid floating on the sea surface. The ice mass thickened as it was compressed by wave crests and thinned as it was stretched out in wave troughs.

As the grease ice grew to a thickness of 7 to 10 cm, the pancake ice began to form. Figure 3.3.1 shows how the pancakes grow with a dish-shaped bottom profile. The pancake surface was covered with a highly saline brine. As the ice grew the temperature of the grease ice was -2.2°C and the surface temperature at the center of the pancakes was 3 to 5°C colder than the water. The low buoyancy of the grease ice plus the raised rims on the pancakes resulted in the pancakes floating so low in the water that their center was slightly below the water line. The density of the grease ice was estimated to be 0.99 g/cc. The pancakes had an average thickness of about 20 mm, and because they were floating in grease ice, their freeboard was only about 1.2 mm rather than 2 mm that could be expected if they were floating in more dense seawater (16). A crude with a density of about 0.9 g/cc would quickly surface in this mixture and easily spread over ice features with such a low freeboard.

Diesel oil was released under water just after the pancakes began to form. The grease ice did not absorb the oil. Rather, the oil immediately came to the surface of the grease ice in the cracks surrounding the pancakes. The oscillatory motion of the pancakes induced by waves pumped the oil laterally from the discharge point through the ice field. Some of the oil pumped up on the

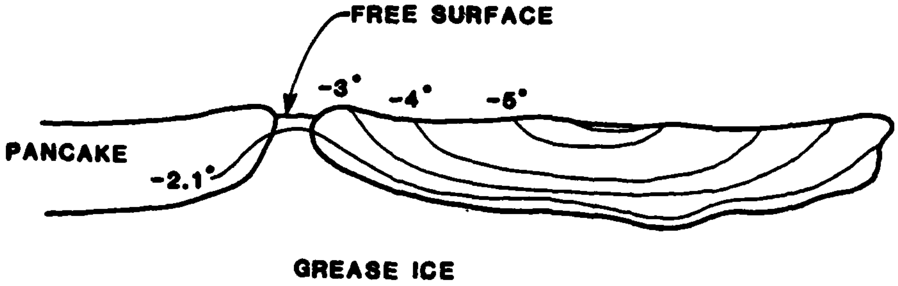

FIGURE 3.3.1 PANCAKE ICE GROWTH
Numbers indicate lines of equal temperature (isotemps) in °C (16).

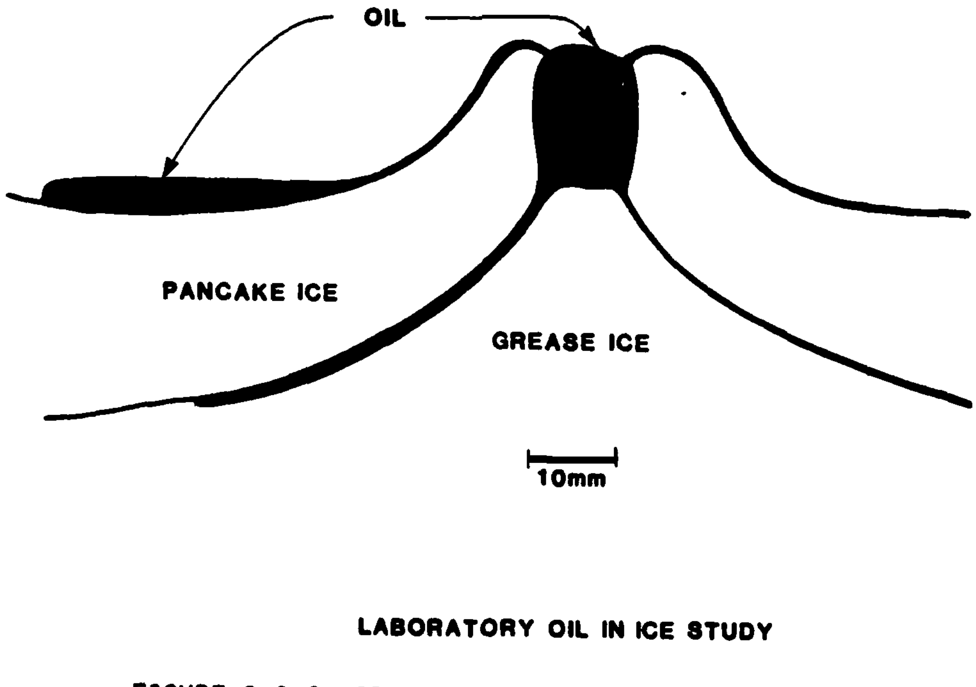

FIGURE 3.3.2 CROSS-SECTION OF PANCAKE ICE AND SPILLED OIL (16)

pancakes was kept in place by the raised rims.

The experiment was then repeated using Prudhoe Bay crude. During this experiment the crude oil was very viscous but it remained fluid. The grease ice thickness was 12 to 13 cm and the pancakes were 10 to 30 mm thick. The oil came up from the bottom of the test tank in viscous slugs resembling poured molasses. In spite of its viscosity, the crude oil went right up through the grease ice and floated on top. Because of the low freeboard of the pancakes, the oil was easily pumped onto the surface of the pancakes and was kept there by the ice rims.

Figure 3.3.2 shows the way the oil was distributed. Most of the oil was in the cracks between the pancakes, but some was on the pancakes, and a smaller amount coated the bottom of the ice with a thin film. (This pattern of distribution of oil in ice is used in Section 5 to calculate the spill carrying capacity of a growing ice field.) About 58% of the test oil had been pumped onto the surface of the pancakes by the time the experiment was completed. Because the sides of the test basin prevented the oil from escaping, the percent of oil on ice in the test tank was probably higher than would be expected in nature.

It was noted that even though the pancakes have a fragile ice structure, they still have brine drainage channels like columnar ice. These channels tend to form when the sea ice is warmed. In this case the room temperature was increased from $-14^{\circ}C$ to $-6^{\circ}C$. This rise in temperature was enough to cause the brine channels to grow to about 3 mm in diameter. Brine channels form easily in pancake ice and provide another path for oil to move up to the surface.

3.3.4 <u>Field Reports of Oil Spreading in Broken Ice</u>

Several field reports describe how spilled oil spread in broken ice in real spill situations. Some of these reports are reviewed here to provide additional background information.

The spill of #2 fuel oil in Buzzard's Bay in 1977 provides an example of a spill of a light refined product in an area covered by relatively thin ice (17). The behavior of #2 fuel oil is similar to what could be expected for diesel; however, the environment in Buzzard's Bay is somewhat different from the Arctic in that the area has a considerable range of tide and high currents.

In the 1977 spill, strong tidal currents transported the oil into a broken ice field and under ice floes. Oil sheens in leads did not collect at the ice edge but rather flowed under the ice edge. The oil was driven under ice by currents of about 1 knot and 24 knot winds. The ice here was about 30 cm thick. In some areas there was brash ice with small ice fragments that were less than 30 mm across and 13 cm thick. This ice did not seem to affect the under ice oil transport.

As breakup began a short time after the spill, oil absorbed in ice features was transported out into Cape Cod Bay. As melting continued, the oil streamed from the ice onto the water in a sheen. In some cases the oil was transported a considerable distance before being released, which extended the area contaminated. Some contaminated floes drifted into beaches where the oil leached out into sediments and beach grass. Oil released from the ice was not weathered, therefore there was a higher potential for adverse impact on the beach.

The spill from the vessel ARROW in Chedabucto Bay, Nova Scotia in February 1970 also illustrates the behavior of oil spilled in an ice environment (18). Although the oil spilled in this case was heavy Bunker C, weathered Prudhoe Bay crude in very cold ambient temperatures could be expected to behave in much the same way.

In several cases the Bunker C from the ARROW followed patterns that could be expected in an arctic environment. For example, floating oil moved against fast ice, which contained it and prevented shoreline contamination. The oil collected in heavy pools along the face of the ice and as the ice grew, the oil became trapped.

In another case, a passage between an island and the mainland was plugged with ice. This ice collected the drifting oil and prevented it from reaching a waterfowl nesting ground.

Some of the oil was trapped in lagoons and was later covered by ice. The oil did not mix with the ice if the lagoon was ice-covered initially. Instead, the oil rode up over the ice and ice-oil-ice sandwiches formed trapping layers of oil 15 cm thick. The oil trapped in the ice remained black and kept the appearance of being fresh (19).

Oil deposited on the surface of ice also moved down through the ice and became trapped. Oil stranded on ice absorbed heat during the day and as a result, melted the ice below, sank down in the ice, then refroze in colder temperatures at night.

Oil also grounded on ice and snow-covered shorelines (19). Thick layers of oil first covered the ice and snow and then the underlying rock and water as melting occurred. Where ice was forming along the shoreline, the oil grew into the crystalline structure. In some cases coarse crystalline ice grew with a light brown color. It contained small oil particles around the ice crystals and small particles of oil in the ice. Some ice grew containing consolidated lumps of oil.

In spite of ample evidence of oil in many varieties of ice, shoreline cleaning by bulldozing was not practical because the oil content was generally less than 5%.

The spill of #6 fuel oil from the tanker KURDISTAN in Cabot Strait in March of 1979 provides one of the only well documented investigations of a spill in relatively heavy subarctic ice conditions (20). A spill of #6 fuel oil is not exactly the same as a spill of crude, but in terms of final density of the oil and appearance of the spill, the #6 fuel is not significantly different from highly weathered crude.

For example, the density of the KURDISTAN spill was found to be 0.987 g/cc at -2°C. (The density of Prudhoe Bay crude is predicted to be 0.938 g/cc after 4 days of weathering.) At the same spill location the density of the ice was measured to be 0.917 g/cc and the sea water was 1.028 g/cc. These numbers lead to two significant conclusions. First, the reserve buoyancy of the floating oil was only 0.04 g/cc, which is very low. This means that the blobs of floating oil could easily be carried under the water surface by wind turbulence or currents, which was in fact, observed. The pancakes of oil were often observed to be covered with a few centimeters of water. In addition, the density of the oil was greater than the density of the ice, so that the patches of oil could easily be carried under the ice. This was also observed.

The offshore pack ice was mixed with large areas of brash ice at

the time of the KURDISTAN spill. The spilled oil tended to mix well with the brash ice. In one spill area, half the oil was mixed in brash ice to a depth of 1 meter and half was stranded on floes. It was estimated that 20% of the surface area of the ice field was contaminated. The contaminated area was estimated to contain about 400 metric tons of oil and cover an area of 2 km2, which is equivalent to a circle with a radius of 0.8 km or 0.4 nautical miles.

The spilled oil was originally concentrated in bands and streaks in the ice and tended to become dispersed and diluted in the pack as time went on. The semi-solid oil was entrained in pack ice and dispersed into progressively smaller particles. The dispersion appeared to be a result of grinding of oil in brash ice by the impact and movement of large floes. Because of this action, the large blobs of heavy oil were reduced to particles from a few centimeters in diameter down to particles of micron size.

Breaking waves in the ice field also had the effect of breaking down accumulations of heavy oil into very fine particles. These particles were later visible as a yellow-brown stain that coated the shoreline.

Oil floating on the water was also splashed up over the edge of the floes by winds and waves. Once on the ice or snow, the oil absorbed a large amount of solar radiation. In one case a temperature of 12^{O}C (54^{O}F) was recorded in oil on ice. This caused the ice to melt and the oil blob to become less viscous and stretch out until the oil divided into successively smaller particles.

Absorption of solar radiation also caused the oil to melt down into the ice. Lower temperatures that occurred periodically resulted in re-freezing over the top and the oil became incorporated in the ice. Evidence of this downward movement came when a hole was dug around a small blob of oil on the surface and a deposit of 10 kg (22 pounds) of oil was found imbedded in the ice.

In some areas the entire floe surface was covered with a film of oil. Figure 3.3.3 shows a picture of one of these areas (20). Also note the heavily contaminated brash ice that surrounds this floe.

Oil was also deposited on the floe surface in small blobs and spatters. In these cases the highest concentrations were within the first meter of the edge. Figure 3.3.4 shows an example of this type of deposit. Just like the larger deposits of oil, these spatters also sink into melt pockets as the oil absorbs solar radiation. Figure 3.3.5 shows a close-up of the oil blobs on a floe surface. These deposits are about 2 cm across.

Some floes were ringed by brash ice that was highly contaminated with oil. This condition may have resulted from concentration of the surface oil as the brash melted. Figure 3.3.6 shows an example of this condition. In some cases the oil in brash ice accumulated in heavily concentrated streaks. Figure 3.3.7 shows an example of this condition.

Larger lumps of oil were observed on floe surfaces, particularly late in the season when the ice had decayed considerably. It is postulated that these accumulations were originally covered with ice or snow and later were exposed by melting. Although it was generally not possible to determine if the underside of the floes were oiled, ships moving through the area overturned large floes and released substantial quantities of oil.

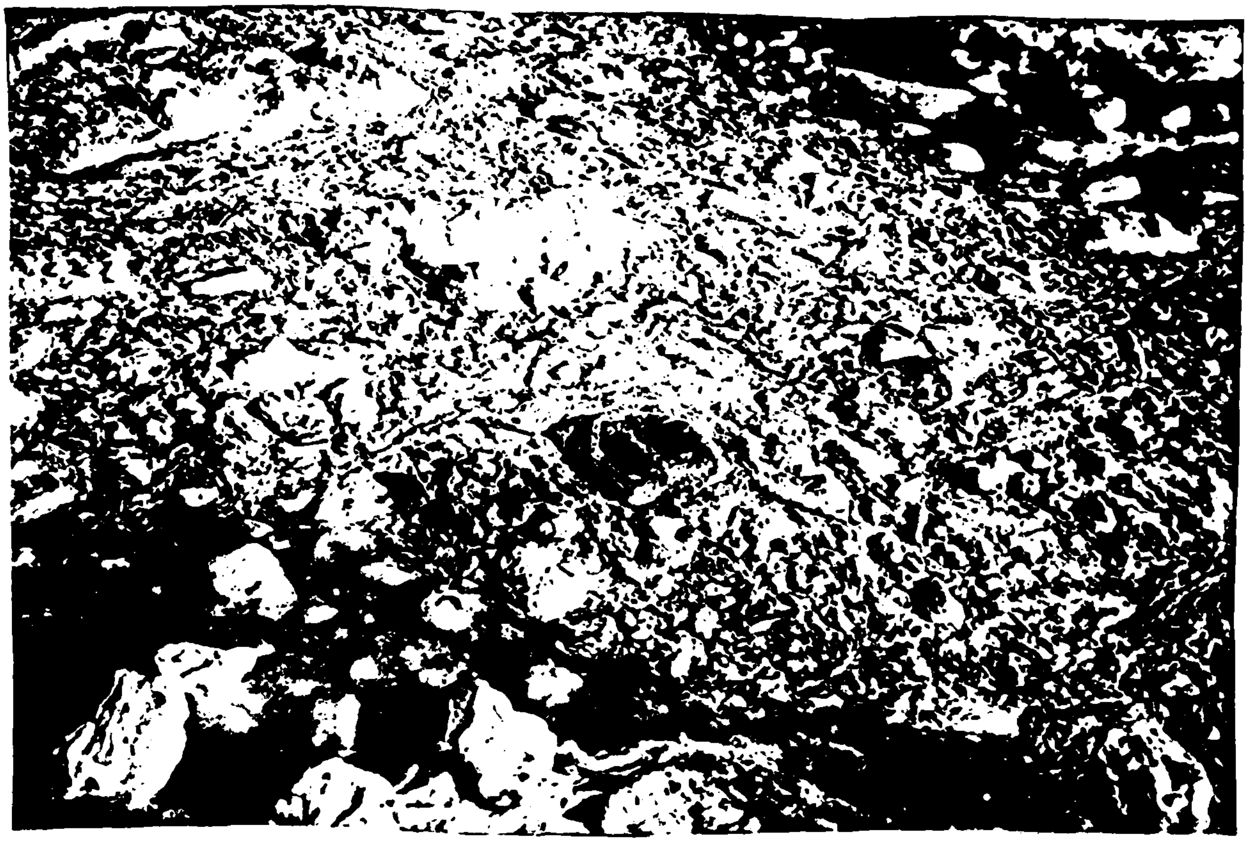

Figure 3.3.3 FLOES TOTALLY COVERED BY A FILM OF OIL. Note tne heavily contaminated brash surrounding this floe (20).

Figure 3.3.4 OIL THROWN OR PUMPED ONTO FLOE SURFACES. The photo shows the melted remains of contaminated brash on a floe edge. The contaminated strip is about 50 cm wide (20).

Figure 3.3.5 OIL BLOBS IN "MELT POCKETS" ON THE FLOE SURFACE. These blobs were about 2 cm across (20).

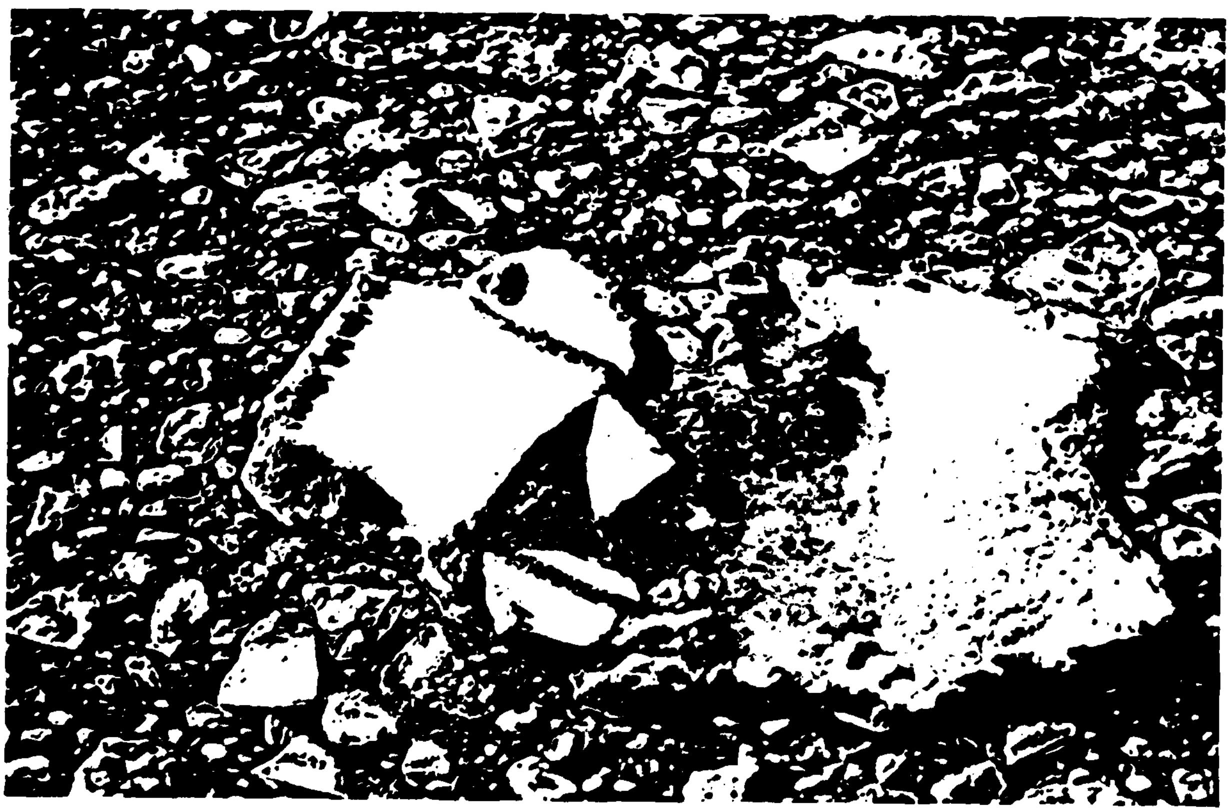

Figure 3.3.6 TYPICAL OF HEAVILY CONTAMINATED AREAS. Mounds of contaminated brash on floe edges had the color and texture of sandpiles. Identification from even a few meters was difficult (20).

Figure 3.3.7 OIL ENTRAINED IN ICE PULP AND BRASH. These accumulations sometimes appeared as long coherent streaks of concentrated oil. The average width of this streak is about 20 cm (20).

3.4 Oil Spreading Under Ice

Concern about the behavior of oil spilled under ice began when the problems of oil spills in the Arctic were first considered. In July of 1970, LTJG Glaeser and LCDR Vance performed an oil under ice experiment in the Chukchi Sea while operating from the U.S. Coast Guard Cutter STATEN ISLAND (4). In the first test the contents of a drum of crude oil were pumped into a pocket under the ice. Although the surface of the ice appeared to be smooth, the underside of the ice was sloping and had caverns. First a hole was drilled in the ice to one of the caverns and oil was pumped down into the hole. The oil did not disperse, but rather rose to the water/ice interface where the oil remained essentially unchanged in one mass.

Next a barrel of oil was released about 3.7 m below the surface at the edge of the large pocket. The oil dispersed in an area of about 0.7 square meters at the oil/water interface. Later the oil spread

over a slightly larger area.

Based on these tests, the investigators concluded that under ice features would be able to contain a fairly large volume of oil providing that non-turbulent flow conditions exist.

These rather simple tests and conclusions marked the beginning of a much larger effort in the scientific community to determine the behavior of oil spilled under ice. It turns out that spill behavior under ice depends on a wide variety of physical parameters including (1) the nature of the under ice surface (i.e., the extent of the skeletal layer), (2) under ice topography, (3) the characteristics of the oil and, (4) under ice currents.

The paragraphs that follow describe spill behavior under ice based on detailed field tests in the Beaufort Sea, characteristics of arctic sea ice, and laboratory tests designed to determine the behavior of oil under ice in the presence of currents.

3.4.1 Typical Spill Behavior Under Ice.

During the winter of 1974-75, NORCOR Engineering performed an important set of arctic oil spill tests in the Canadian Beaufort Sea at Balaena Bay NWT. These tests were significant in themselves and provided the basis for additional work that was to follow (21).

The releases of crude oil under ice at Balaena Bay showed that the behavior of oil under ice is largely a function of under ice topography. Oil rising vertically in the water column collects in the nearby depressions in the ice. If the depressions are large enough, the oil is confined to a single pool. As these depressions are filled, the oil spills over into adjacent depressions.

If the vertically rising oil first encounters a thick section of ice (a dome), then the droplets coalesce into concentric waves of oil that radiate outward from the dome at a reduced velocity. During the tests the rings of oil were observed to surge out from the high point of the dome. Within a few meters of the dome the waves became streams or rivulets of oil. (Figure 3.4.1 shows a sketch of this action based on a black and white photo.)

The outward flow in rivulets was generally unstable and there were occasional breaks in the stream of oil; however, the rivulets tended to follow the same paths, suggesting the path had broken through the skeletal layer of the ice. Occasionally a surge of oil flushed the entire area and then the rivulet pattern was quickly re-established. In these cases no oil contamination of the ice was noted except for a few drops of oil between the flow patterns.

In contrast to the behavior of oil collecting in depressions under ice, oil under flat ice was observed to coalesce into drops similar in appearance to mercury on a glass. In the field tests the crude oil formed drops that were about 8 mm thick. This is an important point to remember because this result has been observed in many under ice tests. Where oil is not collecting in cavities under ice, it can be expected to form a layer that is about 8 mm thick.

In the Balaena Bay tests the the skeletal layer of the growing ice had randomly oriented pockets 5 to 10 cm wide and several centimeters deep. In these areas the oil deposits tended to be 1 to 2 cm deep rather than only 8 mm deep as they would be on flat ice. The distribution of oil under ice varied from small drops to large pools, but 95% of the oil was contained in pools that were more than 1 meter across and

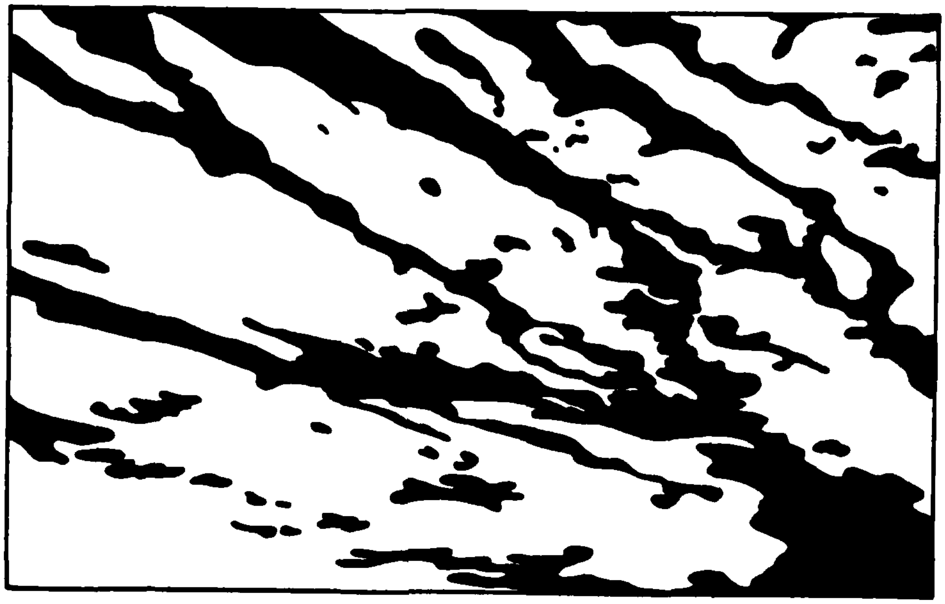

FIGURE 3.4.1 MOVEMENT OF OIL UNDER ICE (21). Sketch based on a photo

had a maximum depth of 20 cm and an average depth of 2 cm.

In 1975 Rosenegger performed a set of oil under ice tests for Environment Canada in the Imperial Oil Limited research laboratory in Calgary, Alberta (22). In these tests the equilibrium thickness of Swan Hills crude (a heavy crude) under ice was 8 mm and the equilibrium thickness of Norman Wells crude (a very light crude) was 8.8 mm. These results tend to confirm the observations in the field tests at Balaena Bay.

3.4.2 Under-Ice Topography

Early field tests of the behavior of oil under ice showed that the under ice surface is not generally flat and that the under ice depressions have the capacity for containing large amounts of oil. The problem, then, is to determine the extent of the under ice irregularities and the amount of oil that can be contained. This section describes under ice topography and the next section presents estimates of how much oil could be contained in typical offshore areas.

In the Balaena Bay tests it was discovered that large scale under-ice irregularities are caused by snow cover (21). Snow insulates and slows ice growth, therefore ice thickness tends to be inversely proportional to snow depth. The depth of the underice features were found to be a function of the stability of the snow accumulations. Only stable, long term, snow features

are able to cause a significant change in under-ice growth.

As an example, at Balaena Bay, an ice sheet 50 cm thick had a variation in thickness of about 20%. By the end of the season this variation amounted to about 35 cm. These variations of ice thickness controlled the thickness of the oil accumulations under ice. For example, a test release of 7.3 m^3 (1620 gallons) of crude oil was not enough to fill a single depression.

The Balaena Bay tests made it clear that under ice topography will determine how much oil can be contained in a given area. Additional field studies were therefore conducted to determine the extent of the variations in ice thickness and to relate these variations to something that can be observed on the surface, such as snow cover (23).

Fast ice grows at a rate of about 1 cm per day until the end of the season when it reaches a thickness of about 2 meters. There are significant variations in this thickness and field studies show that for level fast ice they are related to relatively permanent snow accumulations.

Snow cover on flat fast ice has been found to consist of hard, high density, wind packed snow overlying low density snow. In the U.S. Beaufort Sea, wind drifts are parallel to prevailing northeasterly winds.

In the Canadian Arctic snow ridge patterns form on fast ice in the fall and remain intact throughout the winter (23). The average depth of snow on fast ice is about 22 cm by the end of winter. At Prudhoe Bay the average depth has been observed to be 32 cm. These snow drifts become stationary features basically parallel to the prevailing winds.

In tests performed offshore near Prudhoe Bay, the correlation between snow thickness and ice thickness was best for the Bay and immediately offshore but not quite as good for an adjacent tidal inlet. The snow ridges and ice troughs had nearly the same orientation, 070° true, although trough orientation was somewhat more variable than the snow ridges (23). Both the snow ridges and the ice troughs had an average length of 10 m and a range of lengths of 5 to 20 m.

Aerial photography showed that the snow ridges were stable over a 14 day period. During this time there were winds up to 20 knots with gusts to 30 knots. In spite of these winds, the snow ridges stayed the same.

The correlation between ice thickness and snow depth plus the similarities between snow surface patterns and under ice relief, suggests that snow topography remains stable most of the winter (23). It appears that the snow profile forms early enough in the year to permit ice thickness variations to develop.

The significant thing to note for oil spill response is that not only will the under side of fast ice contain large amounts of oil, <u>the oil will tend to line up with the surface snow patterns with large pockets of oil occurring under thick accumulations of snow.</u>

3.4.3 Under-Ice Storage Capacity

Having determined that large amounts of oil can collect in under ice topography, the next question becomes, how much? During the late-winter ice seasons of 1978, 1979, and 1980, Kovacs surveyed the under-ice relief inside the barrier islands near Prudhoe Bay to determine the potential storage volume for oil (24). These tests showed that the

Table 3.1 Mean Sea Ice Thickness and Potential Under-Ice Pooling Volume at Tigvariak Island (24).

Profile length (m)	Mean thickness (m)	Std dev (m)	Mean vol (m^3/km^2)	Std dev (m^3/km^2)
30	1.497	0.026	33,200	7,660
60	1.541	0.028	29,700	6,750
90	1.539	0.036	31,100	3,540
120	1.544	0.031	29,500	2,240
150	1.546	0.031	32,000	1,590
	1.537*		31,000*	

* Mean of means

mean storage volume for all profile lengths was about 31,000 m^3/km^2. Taken in other units, this is 195,000 bbl per km^2 or 789 bbl per acre. (As another aid to visualize area size, 1 km^2 is very close to the area of a circle with a radius of 0.3 nautical mile.) Table 3.1 shows the mean ice thickness and potential under-ice pooling volume for 18 ice profile segments obtained at Tigvaricik Island (about 70-14N, 147-24W), 23 miles east-south-east of Prudhoe Bay.

In the relatively snow-free area off Reindeer Island the ice bottom was found to be essentially flat. In these conditions it was estimated that a volume of 10,000 m^3/km^2 could be expected to accumulate (This is equivalent to 62,900 bbl/km^2 or 255 bbl/acre.) Note that flat bottom ice without snow cover has about 1/3 the storage capacity of other areas.

At a site near the west dock area, oil pooling capacity was computed to be 60,500 m^3/km^2, which is twice the average capacity. (This is equivalent to 380,545 bbl/km^2 or 1541 bbl/acre.) This increase in storage capacity was attributed to a marked variation in snow cover together with deformation features including ridge keels and refrozen cracks where ice thickness was only 1 m. As before, the thinner ice was found to be under large snow drifts. A refrozen crack 2 m wide provided a large area for the accumulation of oil.

At three more sites inside the barrier islands ice topography was calculated to provide an average of 23,900 m^3/km^2 storage volume. (This is 150,331 bbl/km^2 or 609 bbl/-acre.)

3.4.4 Special Under-Ice Features

In the fast ice zone the bottom topography is generally a function

of variations in ice growth caused by snow cover. Farther out, some gross ice features may result in an even greater carrying capacity for oil spilled under ice. Let's examine how oil may be contained under ice in areas bounded by deep ridge keels in the stamukhi zone and the deep channels under refrozen leads in the pack ice zone.

First consider the stamukhi zone. Typical conditions in this area could include 12 pressure ridges per kilometer with an average keel width of 20 m (25). The undeformed section between ridges is about 63 m and the average keel depth is expected to be about 8 m. (The range of keel depths may be about 4 to 12 m.) Large-scale features such as these have the capacity to hold up to 100,000 bbl (15,876 m^3) of oil.

This estimate of carrying capacity must be accepted with a few reservations. If very large amounts of oil collect in the stamukhi zone, there is an increased probability that the oil will find a way to the surface or become absorbed in unconsolidated ridges. The oil that does find its way to the surface may accumulate in deep pools bounded by the ridge sails.

Flaw leads also provide large-scale under-ice features that have the potential for collecting a large volume of oil. A large flaw lead often forms along the Alaskan Coast near the southern boundary of the moving pack. When such a lead refreezes between floes of thick ice, there is an under ice channel formed that has the capacity to store a large amount of oil.

The ice in refrozen leads is relatively thin and smooth, bounded by walls of ice up to 3 m thick. The lead could be several thousand meters wide and many kilometers long. This geometry may limit the direction of spreading but not the area covered. The lead is therefore likely to be an open-ended sink with a storage volume that is much larger than the volume of oil that is available.

There is also a possibility that the refrozen lead will be deformed again in a short time so that there is an opportunity for the spilled oil to become incorporated in an adjacent pressure ridge (25).

If a blowout occurs under a refrozen lead there is also a high probability that the relatively thin ice will be broken and the oil will fill the lead. If gas is present, ice in the lead will be quickly broken.

Clearly the large-scale ice features that occur outside the fast ice zone have the potential for storing extremely large quantities of oil spilled under ice. The only limitation for storage are the opportunities for the oil to move to the surface or out into other areas.

3.4.5 Oil Movement with Currents

The oil-under-ice experiments conducted at Balaena Bay also included a field assessment of the affect of current on oil under ice (21). Currents under ice in the Beaufort Sea are typically low, so although a current of 15 cm/sec (0.3 kts) was desired for the tests, most currents in the area were only 2 to 5 cm/sec. An area with current of 10 cm/sec (0.2 kts) was finally found and the tests proceeded.

The test consisted of a release of 180 gallons of Norman Wells crude (a very light oil) at a distance of about 5 cm below the ice sheet. The oil spread out in the general direction of the current. The leading edge of the spill advanced then broke into a number of fingers that streamed out until they rejoined to form another pool of oil.

When the oil release stopped, the spreading also stopped. The final spill was about 14 m long and 7 m wide. Oiled areas were separated by clear patches of ice about 0.5 m long and oriented in the direction of the current. The average oil lens thickness was about 6 mm and divers reported that 1 mm droplets of oil were suspended in the water column. The oil moved in a variety of complex shapes from patches of several meters to drops of less than a centimeter. Refer back to Figure 3.4.1 for a typical under-ice spill pattern.

To determine the effect of larger ice features, oil was also released upstream of the pressure ridges. The keel depths of these ridges were 1 to 2 m bounded by depressions and troughs that were up to 0.5 m deep and 8 m wide. As before, the released oil moved with the current in long fingers or rivulets that broke away from the main body of the oil. These fingers were 2 to 5 cm wide and of variable length. The velocity of the oil was between 5 to 7 cm/sec (0.1 to 0.15 kts), which was about half the velocity of the current. The flow in fingers was unstable but tended to follow the same paths indicating there were depressions in the ice. Ice crystals were also reported adjacent to the oil fingers, which indicated that the oil may have been cutting a path in the skeletal layer. When the oil reached a trough it flowed parallel to the pressure ridge and gathered in a pool. When the release was completed, the pool of oil measured 6 m by 3 m and was about 10 cm deep. Once in the pool the oil stabilized and did not appear to be affected by the current.

In 1980 Cox performed controlled spill tests for NOAA in a large laboratory flow tank to determine the affect of current on oil under ice (26, 27). Although these tests were performed with #2, #4, and #5 fuel oils, the results can be used to make generalizations about spill behavior of other products. For example, the static slick thickness under smooth ice for the products tested turned out to be 5 mm, 9 mm, and 10 mm for the products in the order mentioned. These results compare favorably with the field tests of crude oil that generally had an equilibrium thickness of about 8 mm under smooth ice.

The laboratory tests then determined the threshold current velocity required to move oil under ice based on under ice roughness. For smooth ice, the threshold velocity is very low, less than 0.1 kts. However, because smooth ice must have roughness elements that are less than the equilibrium thickness of the slick (that is, less than about 8 mm), smooth ice by this definition is not likely to occur in nature. There is more concern, therefore for spill behavior under ice that has large roughness elements.

Large roughness elements have the potential of totally restraining an advancing slick up to some critical value of current velocity. Figure 3.4.2 shows the shape that is taken by a slick confined by a large roughness element (27). The figure shows that there are three regions in the trapped slick, (1) the head region, (2) the neck region, and (3) the tail region. The dimensions of these features are a function of current velocity for each type of oil.

Oil can be released from this shape in two ways. First, when the slick length and thickness exceed the equilibrium point for the flow, leakage occurs at the tail region until the equilibrium volume is restored. The second failure consists of total flushing of the oil from behind the obstruction by high current velocities. In this case, the head wave is continually being rebuilt

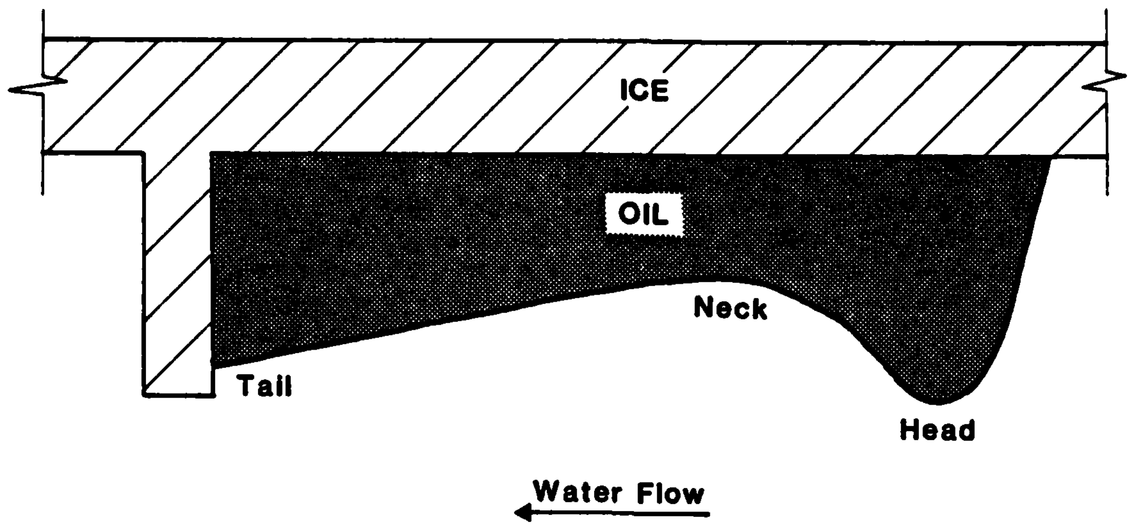

FIGURE 3.4.2 OIL CONFINED BY A LARGE ROUGHNESS ELEMENT

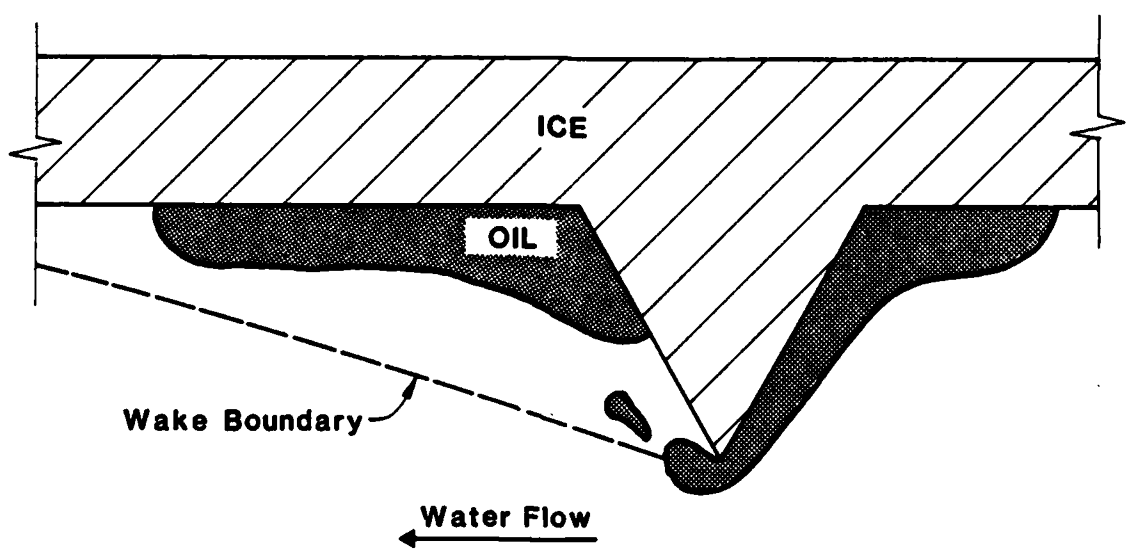

FIGURE 3.4.3 OIL LEAKAGE BY A LARGE ROUGHNESS ELEMENT

by the flow as oil is being torn away, and the slick gradually decreases in length until the slick is entirely flushed out. This failure velocity was found to be essentially independent of the obstruction depth and obstruction angle. For Prudhoe Bay crude and arctic diesel the failure velocity would be about 22 cm/sec, which is a little more than 0.4 kts.

Velocity failure tests were performed for two different barrier geometries; the vertical barriers shown in Figure 3.4.2 and a wedge shaped barrier with an angle of 32^{o} from the horizontal shown in Figure 3.4.3. The important discovery in these tests was that there are no differences in the containment ability of these barriers. The oil buoyancy is very important to containment, so that even mild slopes present a formidable barrier to the advance of the slick.

Figure 3.4.3 also shows the path taken by the oil as it is flushed out from behind the barrier. Notice that the oil leaking from behind the barrier was not picked up by the free stream and carried away. Instead, the strong buoyant forces caused some of the oil to rise into the wake region behind the roughness element. The holding capacity of the wake appeared to be equal to the equilibrium slick thickness spread over about 70% of the length of the wake. If water current velocities are greater than the frontal flushing velocity, oil containment in the wake region down-stream of a large roughness element also fails. The time required for failure may be a matter of minutes or hours, but there is negligible long term containment capacity in the downstream area.

The laboratory work also included tests to determine the volume of oil that could be held in a small cavity in the ice. For the purposes of the tests, cavities were defined as spaces between roughness peaks that are short enough for an oil slick to span the entire opening. (This depends on the current velocity.) It was found that in the presence of a current, cavities in ice cannot totally fill with oil, but they can partially contain oil even for current velocities exceeding values that would cause containment failure for a single large obstruction.

In summary, these tests show that a current of 0.4 kts is needed to move oil in the presence of under ice roughness. Further, it was shown that the shape of the roughness element is not important. The study found that oil escaping from a barrier because of high current velocity is likely to collect just down stream of the barrier, but the time the oil will remain in this area is likely to be relatively short. Finally, it was found that cavities in ice can collect oil even when current velocities exceed the critical velocity for containment behind a single barrier, but in these cases the cavity will not be completely filled with oil. <u>In the Arctic, the velocity of under-ice currents is generally less than the threshold velocity for oil movement, therefore oil spilled under ice is not likely to move because of currents.</u>

3.5 Oil Spreading on Ice and Snow

The On Scene Coordinator may encounter cases of oil spilling on ice. The overall consideration in dealing with these spills is that ice is likely to inhibit spreading. The degree to which spreading is restricted depends on ice topography, the condition of the ice, and the amount of snow cover. Oil spreading on ice is therefore described in terms of ice type. Oil spreading in snow will be covered separately.

3.5.1 Spreading on Winter Ice

The Coast Guard performed tests of Prudhoe Bay crude oil spilled on hard winter ice on the Bering Sea and Port Clarence Bay during January and February of 1972 (2). Although there are some other reports of actual spills on winter ice, these tests provide the best description of the behavior of crude oil on ice.

The test oil at Port Clarence had a specific gravity of 0.890 g/cc and was close to room temperature (+56°F, or 13.3°C) when it was released on level ice. The ice was 2 to 3 feet thick (61 to 91 cm) and was covered by 8 inches (20 cm) of snow. The air temperature was about -10°F (-23°C) and sometimes reached an extreme low of -40°F (-40°C).

The pattern of the oil spreading on the ice was carefully recorded. This result was compared to a theoretical equation describing spreading on ice and it was also used to develop an empirical equation that described exactly what happened during those tests. These two equations agreed quite well, with the empirical equation showing a smaller radius of spreading than the theoretical equation. This is to be expected because in a real situation the topography of the ice and the presence of snow can be expected to reduce the area of spreading. The empirical equation describing the test spill is as follows:

$$R=1.3(Q^3g)^{0.1}T^{0.5}$$

where,

R= spill radius in m
Q= spill rate in m^3/sec
T= time in seconds
g= gravity

This equation represents the best description of crude oil spreading on ice that is available at this time. It records what happened in a real situation in a typical environment, which makes it more acceptable than a purely theoretical equation. But even though the level of confidence in this result is high, the reader should be cautioned that an exact solution to the problem of oil spreading on ice cannot be expected. Scaling small tests to large scale spills is a significant problem. It is therefore perfectly legitimate to question whether the Port Clarence results can be extended to describe large spills. The answer is possibly not, but right now this equation represents the best information that is available.

Figure 3.5.1 shows a plot of the equation for a set of typical spill rates. The spill radius plotted may be considered to be the worst case. If ice topography is highly irregular or if there are large accumulations of snow, the oil will cover a smaller area. The theory of oil spreading on ice indicates that the smallest terminal thickness of the spill will be about 3.5 mm (2). In the tests the oil spread to an average terminal thickness of 5 mm (28). The number circled on each curve represents an estimated terminal thickness for each spill. Based on the test results, the terminal thickness is not likely to go below 5 mm. Also, for a continuous spill the oil is likely to "stack up" near the source and be much thicker than the estimate. If the spill is chilled by low air temperatures and ice temperatures, spreading may be reduced. This will result in thicker accumulations of oil and a smaller spill radius.

The nature of the environment is another significant variable in the spreading process. The ice topography and the nature of the ice probably affects oil spreading more than any other factor. The spreading of oil on ice may be significantly different from what is described in this equation if the oil pools on ice, if it fills cracks in the ice, or if it is absorbed by heavy

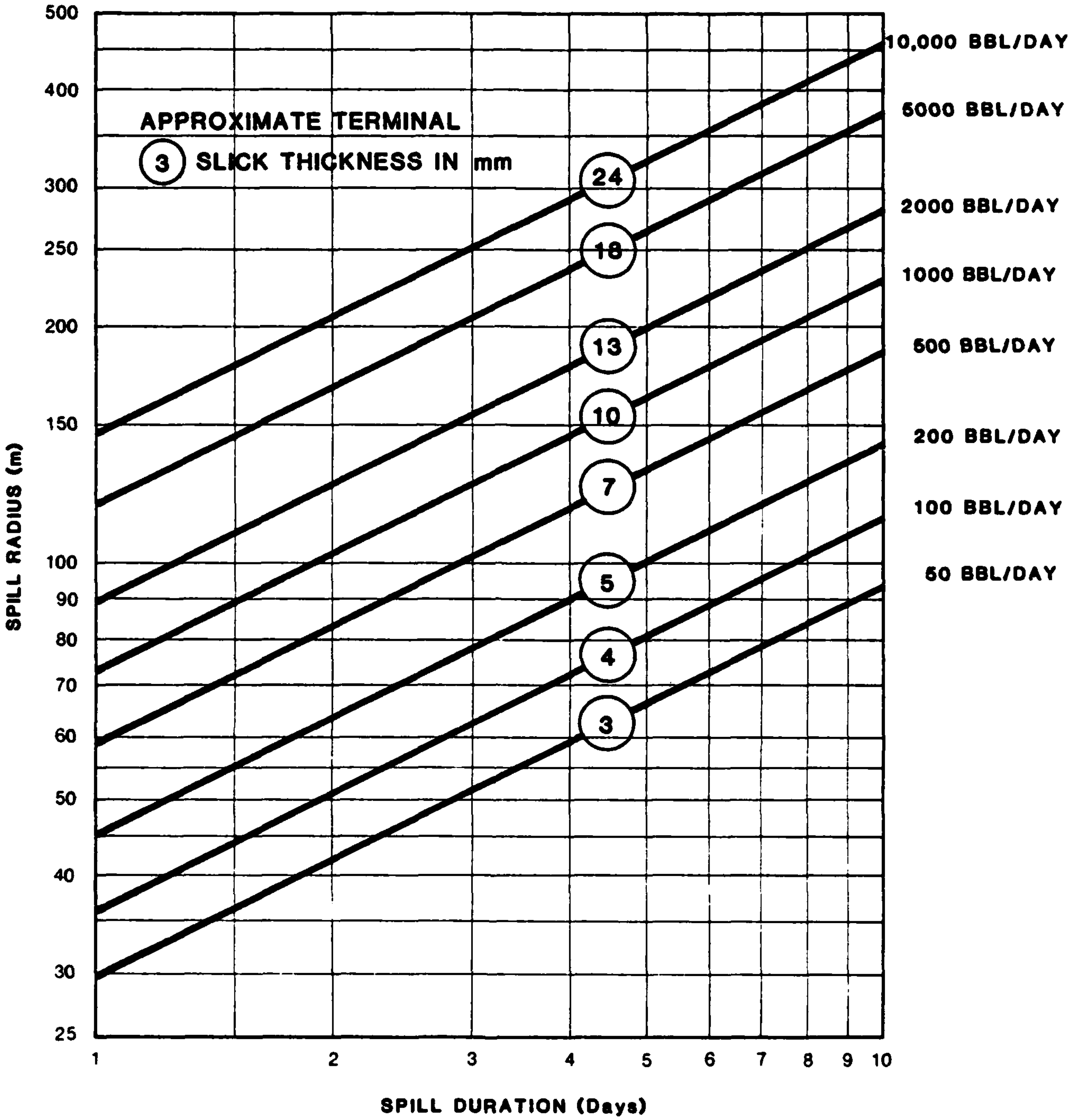

FIGURE 3.5.1 RADIUS OF A CRUDE OIL SPILL SPREADING ON WINTER ICE (2). Curves are based on winter sea ice tests performed with Prudhoe Bay crude at 13.3°C (56°F) in ambient air temperatures of -23°C to -40°C (-10°F to -40° F). The ice was essentially level and had a snow cover of about 20 cm (8 inches).

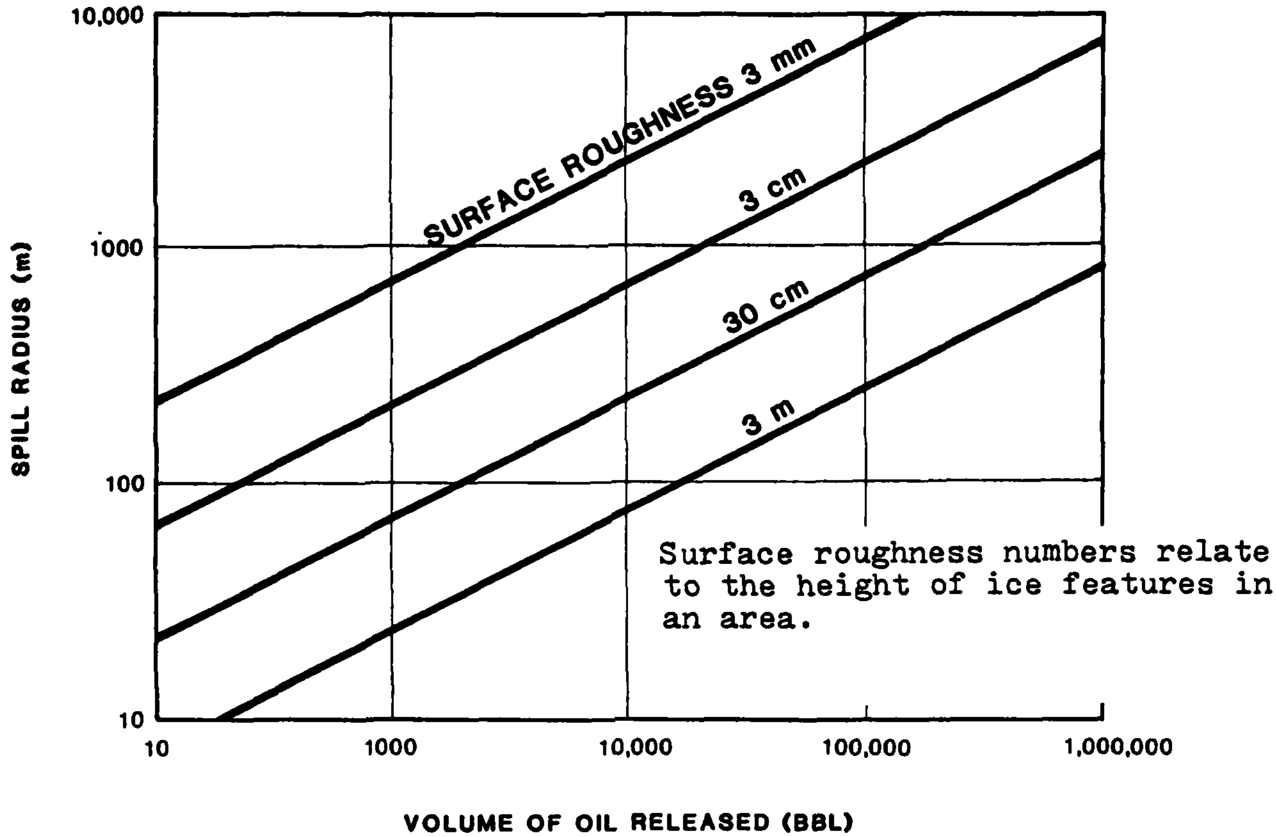

FIGURE 3.5.2 SPILL RADIUS CONSIDERING SURFACE ROUGHNESS OF WINTER ICE (28). These curves show the estimated radius of Prudhoe Bay crude spreading on hard winter ice under varying conditions of roughness. Tests were performed with oil at 13.3°C (56°F) and air temperatures varying between -23°C to -40°C (-10°F and -40°F).

snow. This may cause the reader concern, but in nearly every case spreading will be less than described in the equation, so the error is on the safe side.

Figure 3.5.2 shows how the radius of a spill can be expected to change as a function of the effective surface roughness height of the ice (28). These curves are also based on the Port Clarence tests. In this case an instantaneous spill is assumed rather than a continuous spill. Since ice topography is likely to be highly variable from place to place, season to season, and year to year, determining the area covered by the spill is less precise than for a spill on smooth ice. The important point to remember, however, is that irregular topography will tend to hold more oil and the spill will cover a smaller area.

It is significant to note that oil poured on winter snow and ice did not migrate downward (28). Instead, the oil melted the interfacial snow, which drained down into the channels of the ice where it refroze and blocked any downward migration of the oil. The oil remained as a surface layer, and when covered by snow, formed

an oil/snow mulch that was 80% water by volume. This behavior is significantly different from that which occurred when crude oil was released on porous summer ice. The tests on summer ice are described in the section that follows.

There are a few other aspects of oil spreading on winter ice that are of lesser importance and are described briefly.

Mackay and others performed a set of tests from 1972 to 1974 to show the physical effect of crude oil spills on the terrain of the Mackenzie Valley, NWT (29). These small scale tests show that oil temperature has an affect on spreading, with warm oil spreading to cover a greater area than colder oil. Also ice temperature has some affect on spreading, with colder ice inhibiting spreading. The influence of the ice temperature appears to be appreciably less than the oil temperature. These tests also showed that when hot oil spills on ice, it melts some of the ice and spreading is enhanced by the film of water that occurs between the oil and the ice.

These results are not used to estimate behavior in large spills because the tests were designed to show spreading over frozen ground that had some patches of ice rather than continuous ice, and because the tests were on a very small scale, involving milliliters of oil spreading over square centimeters of ground.

A final aspect of oil spreading over hard winter ice concerns light oils being driven by winds over relatively smooth, unobstructed ice. In a spill of arctic diesel on the ice of Hudson Bay, Canada, high winds were reported to carry the oil at velocities of up to 30 cm/sec (0.6 knots) over the ice (30). Although this speed is high, it is considerably lower than the speeds of light products moving under the force of winds over water. In very high winds (40 to 50 kts), droplets of oil may also be blown to great distances over the surface of the ice. In the spill at Buzzard's Bay, Massachusetts in 1977, high winds were reported to blow the thin, surface coating of #2 fuel oil over nearly clear ice even though the oil penetrated the ice to a depth of about 3 mm (17).

Spill experience at Hudson Bay and Buzzard's Bay shows that high winds may drive light oil over ice, but these results cannot be applied directly to the Beaufort Sea because of differences in the ice characteristics. Beaufort Sea ice generally has a very high surface salinity and an interior salinity of about 8 o/oo. The ice at Buzzard's Bay had a very low surface salinity and an interior salinity of about 4 o/oo, so its hardness was similar to fresh water ice. Light oil could therefore be expected to penetrate deeper into arctic sea ice than the ice at Buzzard's Bay. The extent of the penetration would depend on the season and the structure of the sea ice.

In summer, then, high winds may drive a very light oil over clear, hard (not porous), unobstructed ice. For example, arctic diesel might be blown over ice, but Prudhoe Bay crude, with a pour point of about -10°C, would not. Porous ice, rubble fields, pressure ridges, and accumulations of snow would prevent any significant wind movement of oil over ice.

3.5.2 Spreading on Summer Ice

Oil spill tests were conducted in the Chukchi Sea from a Coast Guard Cutter in July 1970 (4). The environmental conditions produced significantly different results from the tests of oil spreading on hard winter ice. Air temperatures were much higher, -0.6 to 11.1°C (31 to 52°F). The surface of the ice was soft and irreg-

ular, and the ice had begun to deteriorate. It looked like snow but it could support a considerable weight. In this case the oil released on the surface was quickly absorbed into the ice. When fully saturated, the ice absorbed about 25% of its volume in oil. The most heavily saturated areas were close to the spill and the percent oil in the ice decreased out near the edges.

The ice was permeable enough to let the oil drain to lower levels with gravity. As the ice melted, the oil gradually collected in melt ponds, although a large portion remained in the ice.

These tests do not provide a quantative measure of how oil can be expected to spread on soft summer ice. It is probably sufficient to say that the area covered by the oil will be small as compared to a similar spill on hard winter ice. Although the tests do not report what may happen to the oil over a longer term, a knowledge of sea ice properties in July permit one to make some realistic assumptions.

The ice described in the tests was in an advanced stage of decay. Break-up was close at hand. If the ice were heavily oiled, the reduction in albedo would make it decay even faster. (Albedo is the ratio of light reflected from a surface to the total light falling on the surface. Dark surfaces have low albedo; that is, they absorb more energy and become warm.) Thus rather than spreading, the oil is likely to settle into melt pools. If a flow of oil and melt-water develops adjacent to the pools, whirl-pools may develop that draw the oil to the low spot and they may even transport it under the ice. Projection of oil under ice by whirl-pools was observed in a spill on ice in Norway in 1979, and an analysis shows that the acceleration of these water jets may transport the oil 2 m down into the water (31).

Oil on summer ice, therefore, is expected to behave far differently than oil spilled on hard winter ice. In summer, particularly near break-up, the oil will follow the path of the melting water: it will tend to cover the surface of melting ice; it will move from pool to pool with the water; it will follow the vortex flow of the water down through the ice; it will follow the water spilling off the ice into leads; and it may even be blown by the wind over the water pooled on the ice.

In short, oil moving on melting ice at break-up time becomes a big problem for the On Scene Coordinator. Whereas the winter ice provides a barrier to oil movement, summer ice provides many paths for it to flow, and the melting ice may even accelerate its flow into new, previously inaccessible areas. Breakup can turn the slow routine of winter cleanup on ice into a real disaster. The prospect of uncontrolled spill movement at breakup emphasizes the importance of a maximum response effort while the ice is still secure.

3.5.3 Spreading on Snow

In general, snow absorbs spilled oil and prevents its movement. Recognizing this property, Allen has used snow as a sorbent to recover oil in tests and in actual spill situations (32.) The precise way that the snow will react with spilled oil is difficult to determine because it depends on the characteristics of the snow, the oil, and environmental conditions, particularly temperature. Here is what can be expected to happen in typical spill situations based on field tests.

In the winter test conducted at Port Clarence, oil at 13°C (56°F) was poured on a snow surface that had a temperature that varied between

-15 and $-26^{O}C$ ($+5^{O}F$ and $-15^{O}F$). The warm oil caused the snow to melt and the resulting water moved down into the pores of the snow where it froze and prevented the downward migration of the oil (2). No additional downward migration was noted in the next 30 days. (The reader should recall that these tests occurred in January and February. If the released oil had been observed until the spring thaw occurred, melting would have permitted the oil to move down into the snow.)

Soon after the oil release at Port Clarence, the layer of oil on the snow was covered with wind-blown snow. The snow cover migrated down into the oil forming an oil/snow crystalline mulch that was 80% water by volume. The mulch was cohesive and could be easily removed by shoveling or scraping. As the temperature increased above the pour point of the oil (about $-10^{O}C$), the spill became more fluid and separated out of the mulch. Later heavy snowfalls resulted in a rapid accumulation of compacted snow on the surface of the oil. It appeared to the test observers that this additional layer of compacted snow reduced the volume of snow infiltrating into the oil.

Nelson and Allen conducted another test of the behavior of oil on snow near West Dock at Prudhoe Bay on 16 April 1981 (32). Crude oil at 48°C was sprayed into the air to examine the physical interaction of the oil with snow under cold ambient air temperature and under warmer conditions. In the first case (16 April), the air temperature was $-23^{O}C$. The snow at that time was quite firm and would support foot traffic with little deformation. The oil did not penetrate into the snow to a depth greater than 5 cm. A more typical penetration depth was 1 cm because the oil cooled rapidly and because of the dense crust of the snow below.

Two weeks later another test was performed in an air temperature of $4^{O}C$. The snow structure had deteriorated to the point that it was nearly saturated with melted water and would not support foot traffic. In this case the oil saturated the snow to a much greater extent.

Basically these tests, and tests performed in Canada by Mackay in 1972 and 1973 with other types of crudes (33), show that snow acts as a sorbent. The extent to which the snow can restrict the spreading of a spill depends on its capacity to absorb oil. This capacity depends, in turn, on the void space in the snow and the extent to which the snow can become saturated. In the Canadian tests the snow was found to have a void space of 60 to 85% (with an average of about 75%) and it became about 25 to 55% saturated with oil (the average was about 40%).

The problem now becomes how to predict the absorption capacity of snow based on these data. In a personal communication, Dr. Mackay of the University of Toronto suggested that it would be possible to compute the area covered by a spill of oil on snow by using average porosity and average saturation to determine how much oil would be required to fill the voids. This has been done using the average values for void space and porosity mentioned above. The result is shown in Figure 3.5.3. This set of curves gives the expected radius of a spill on snow based on the expected absorption capacity of the snow. It must be emphasized that these results only reflect the expected absorption capacity of the snow and not the containment capacity of any other ice features. These curves could be helpful in determining the radius of the spill when absorption by snow is the principal containment feature. The results cannot necessarily be compared to or combined with the curves shown in Figures 3.5.1 or

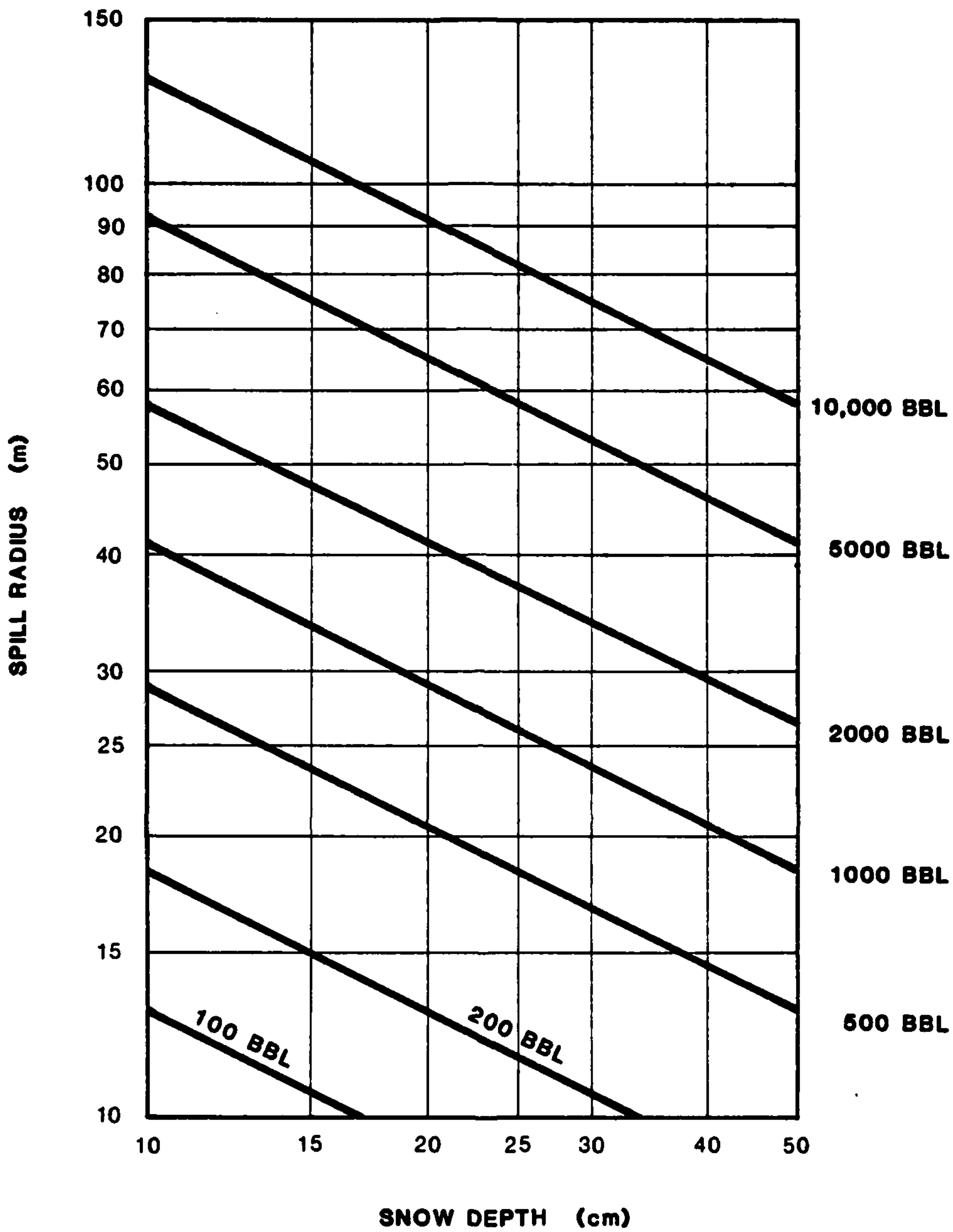

FIGURE 3.5.3 ABSORPTION CAPACITY OF SNOW. These curves show typical absorption capacity of snow using an average snow void space of 75% and an average saturation capacity of 40%.

3.5.2. Figure 3.5.3 is simply an aid in estimating the carrying capacity of snow.

It can also be noted that snow can effectively restrict the horizontal movement of oil on ice. In the 1974-1975 test performed at the Balaena Bay in the Canadian Beaufort Sea, oil drums were used to catch wind-driven snow and build a snow berm around a spill test area. The snow drifted around the barrels to form a barrier about 1 m high and 3 m wide (21). The snow was effective in containing the oil spilled on ice during the tests. It was found that the oil did not penetrate the snow berm more than 15 to 20 cm. This shows that snow can even be used as a barrier to oil spreading on ice.

In the Buzzard's Bay spill of #2 fuel oil, a snow storm covered the oil pooled on ice and resulted in a slush-like mixture that was 30% oil by volume (17). This mixture could be picked up by hand without any oil dripping free. In some cases the snow was not absorbed into the oil and the result was an ice/oil/ice sandwich.

3.6 Spill Behavior in a Blowout

Nearly all of the information on undersea blowouts comes from field tests and engineering studies. In this area, the field tests and analysis performed by D.R. Topham for the Canadian Beaufort Sea Project in 1975 provides the basis for all currently accepted undersea blowout predictions (34). The work done by Topham also provided the starting point for additional interpretation and application of results to other situations. Later experiments performed in sea ice in the Canadian Beaufort Sea expand on the origional work done by Topham.

This section describes the results of Topham's experiments and analysis as they apply to potential undersea blowout situations in the Alaskan Beaufort Sea. Further, the section also describes the significant interpretations of Topham's experiments and the results of the later tests that were performed in ice in the Beaufort Sea. Finally, the section describes the results of an engineering analysis that predicts the bahavior of airborne particles of a surface blowout. This analysis is needed to predict the area contaminated and the fate of the airborne products of a surface blowout.

3.6.1 Undersea Blowout

An undersea blowout may occur when a drill bit strikes a high pressure pocket of oil or gas deep in the earth (35). For purposes of analysis and planning, the standard blowout for the Canadian Beaufort Sea has been assumed to have a flow rate of 2500 barrels per day with a gas to oil ratio of 150 to 1. It is not suggested that this flow rate is either average or typical. Rather it is mentioned because this rate has already been used in many field experiments and in making baseline predictions. The results of these tests can also be used for other situations involving different flow rates.

Baseline Studies. The study of undersea blowouts began with a full scale simulation performed by pumping large volumes of air at atmospheric pressure down to depths of 60 m and 23 m of seawater and measuring the resulting flow patterns (34). These tests provided the information for the original analysis of undersea blowout spill behavior.

The undersea field experiment showed that oil ejected under pressure from an undersea orifice is shattered into droplets within a short distance of their source. A major portion of the droplets in this experiment

had a diameter of about 1 mm and a much smaller portion (about 1%) had a diameter of .05 mm or less. If the oil were released without gas pressure, the droplets could be expected to have a diameter of about 1 cm with very little variation (35).

There is some concern that as the oil is ejected the gas could be a source of energy to form emulsions. Experiments show that this energy would not be applied in a way that would develop emulsions; therefore, the oil is expected to come to the surface as slick (35).

The full scale tests provided some important information about flow patterns as the oil rises in the water column. It was found that the flow of the central plume was conical until rising to a height of 23 m, then the radius remained approximately constant with some additional expansion as it broke the surface (34). The interaction of the plume with the surface produced a ring of waves concentric with the plume center. This pattern was formed by flow outward to the ring of waves, some downward flow at the ring, and inward flow in the area immediately beyond the ring.

Figure 3.6.1 provides a simplified sketch of what was observed. Region I shows a conical plume in which the gas emerging from the sea bed expands causing the oil to become finely divided (35). This expansion helps to keep the oil particles at a nearly uniform size of 1 mm. In Region II the blowout products rise in a cylindrical column where there is relatively constant velocity upward along the centerline of the system. In very shallow areas only conical flow would occur because cylindrical flow begins about 23 m from the bottom. In Region III most of the gas escapes to the atmosphere, and strong radial currents occur out to a characteristic radius, then flow down carrying small gas bubbles and oil particles to a depth of a few meters. There has been speculation that the wave ring would provide some spill containment in a blowout.

The circulation in these three flow regions is not necessarily a steady state (35). Instead, both the conical and cylindrical flow regions could be expected to fluctuate violently both in position and fluid velocities.

Based on a study performed by the Newfoundland Mines and Energy Department, Thornton reports that the flow near the point of oil release has the character of a jet that entrains water and loses its intial velocity (36). Velocity decay is very rapid. Velocities are only a few meters per second at a vertical distance of less than 10 m from the source of the oil. Buoyancy is the only vertical driving force in the region of 10 to 20 m from the bottom. The gas bubbles expand as they rise through the water column, entrain water, and create an upward current or water plume that entrains the more slowly rising oil droplets. When gas bubbles reach a limiting size they break up. The maximum diameter is probably about 1 to 3 cm. Single bubbles of this size range would have terminal velocities of 0.3 to 0.6 m/s if they were separated from the plume. The theory predicts an average plume velocity of about 1 m/s, so that for a blowout in shallow water (about 30 m), the oil would reach the surface in about 30 seconds.

The wave ring in Region III can be characterized as a boil area surrounded by outwardly directed surface currents that terminate in a wave ring (36). (See Figure 3.6.1.) At the wave ring the outward flowing currents from inside the ring meet the inward flowing currents from outside the ring to produce a vertical,

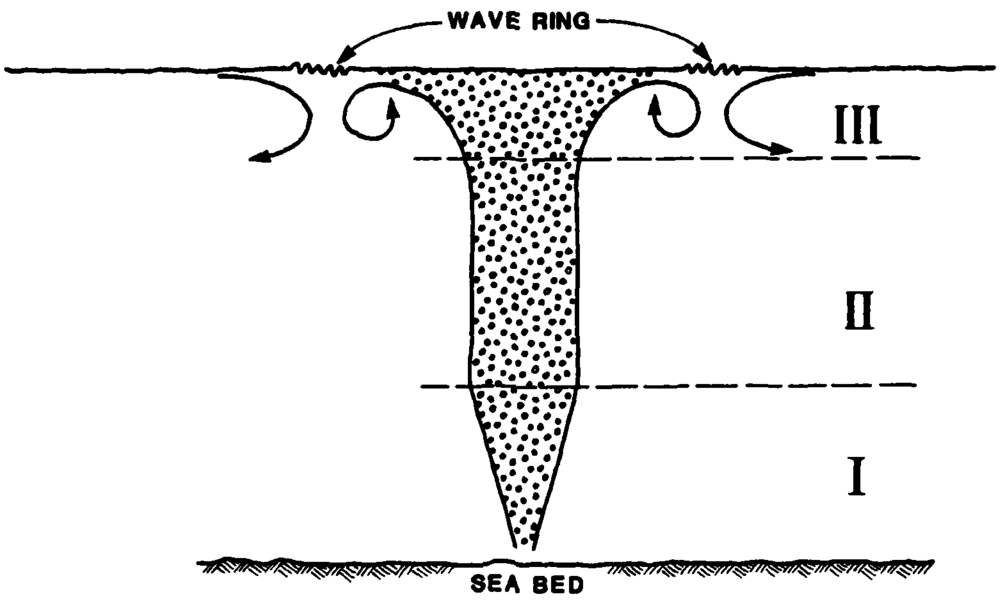

FIGURE 3.6.1 CIRCULATION IN AN UNDERSEA BLOWOUT (35)

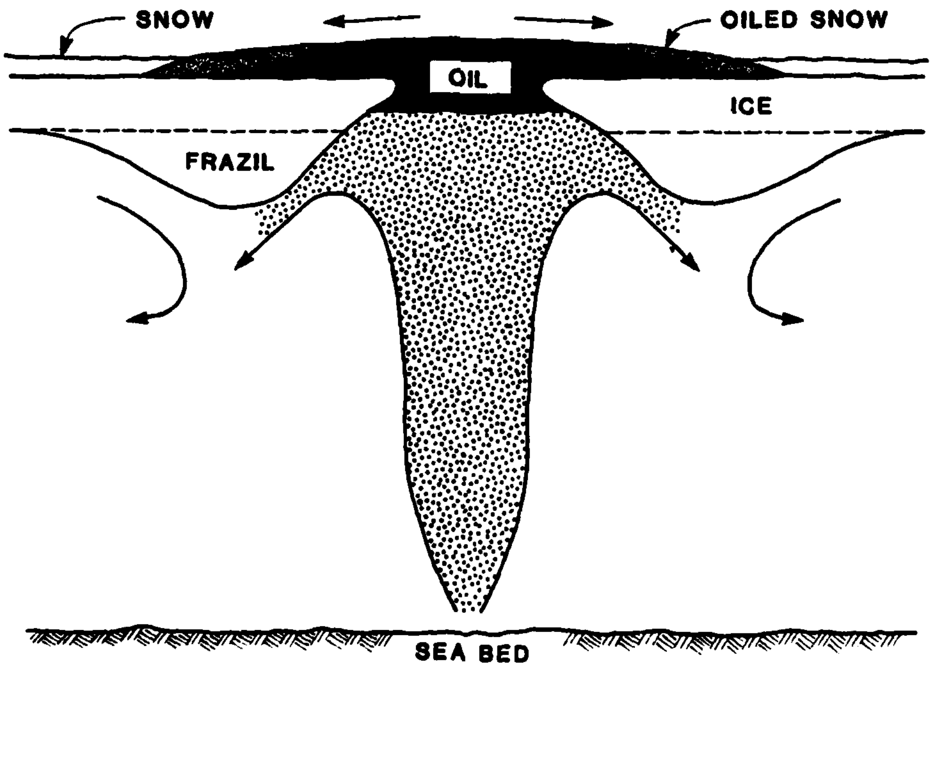

FIGURE 3.6.3 BLOWOUT UNDER FAST ICE (35)

downward flowing current. In the tests, some of the bubbles at the wave ring were observed to mix to a depth of 12 m (34).

Oil inside the wave ring would be swept out to the perimeter by a 0.5 m/s surface current and would tend to collect there because of the inward current of about 0.2 m/s outside the wave ring (36). <u>Once the oil thickness exceeded about 1 to 2 cm inside the ring, the potential head associated with the oil would overcome the velocity head of the containing current and oil would begin to escape</u>. Even before this occurred, local currents of more than 0.2 m/s (0.4 kts) would cause oil to leak from the downstream side of the wave ring. Winds would also tend to cause leaking from the wave ring.

Some of the vertically rising oil droplets would emerge outside the wave ring. Some of these would be carried into the ring by the locally inward directed currents, but others would surface too far away and therefore would be carried away by local winds and currents.

The precise behavior of oil on the surface over a blowout is not known, but it seems likely that a significant proportion of the oil would be carried outside the wave ring (36). Even for a shallow water blowout, oil droplets are likely to be carried thousands of meters downstream in a current of just 0.5 kts.

Topham developed an empirical equation to predict the wave ring radius as a part of the original field experiments (34). This equation will help the OSC to estimate the size of wave ring to be expected in various depths of water. The wave ring radius is given by the following:

$$R=0.39Z[V_f X 10.36/(Z+10.36)]^{1/3}$$

where R=wave ring radius in meters
Z=water depth in meters
V_f=volume of gas flow in m^3/minute

Figure 3.6.2 provides a plot of this equation for representative water depths. For the accepted blowout rate of 2500 bbl/day (398 m^3/day) there is a gas flow rate of about 41 m^3/min. In a water depth of 20 m, the wave ring radius would be about 18 m. This result checks out very well with tests performed in the Canadian Beaufort Sea, which are described in Section 3.6.3.

3.6.2 Under-Ice Blowout

In his hypothesis for a blowout under ice, Lewis suggests that the gas collecting under the ice sheet will raise it slightly, and eventually find a place to penetrate the ice and escape (35). The heat of the oil would melt the ice at a rate of a few centimeters a day or would prevent freezing if the blowout occurred early in the season. This would maintain an open pool above the blowout, which would help to keep the oil in place.

If the ice over the blowout does not fail, Lewis believes the oil would collect in a ring over the blowout until it reaches a thickness at which the hydrostatic pressure of the oil exceeds the force of hydrodynamic containment (35). The oil would then move outward until the escape of oil balances the input from below. Oil moving out would fill the irregularities in the ice. As the voids are filled, the oil would run out again and find new cavities. This now becomes a problem of behavior of oil under ice.

Early in the year oil surfacing into openings in the ice would be

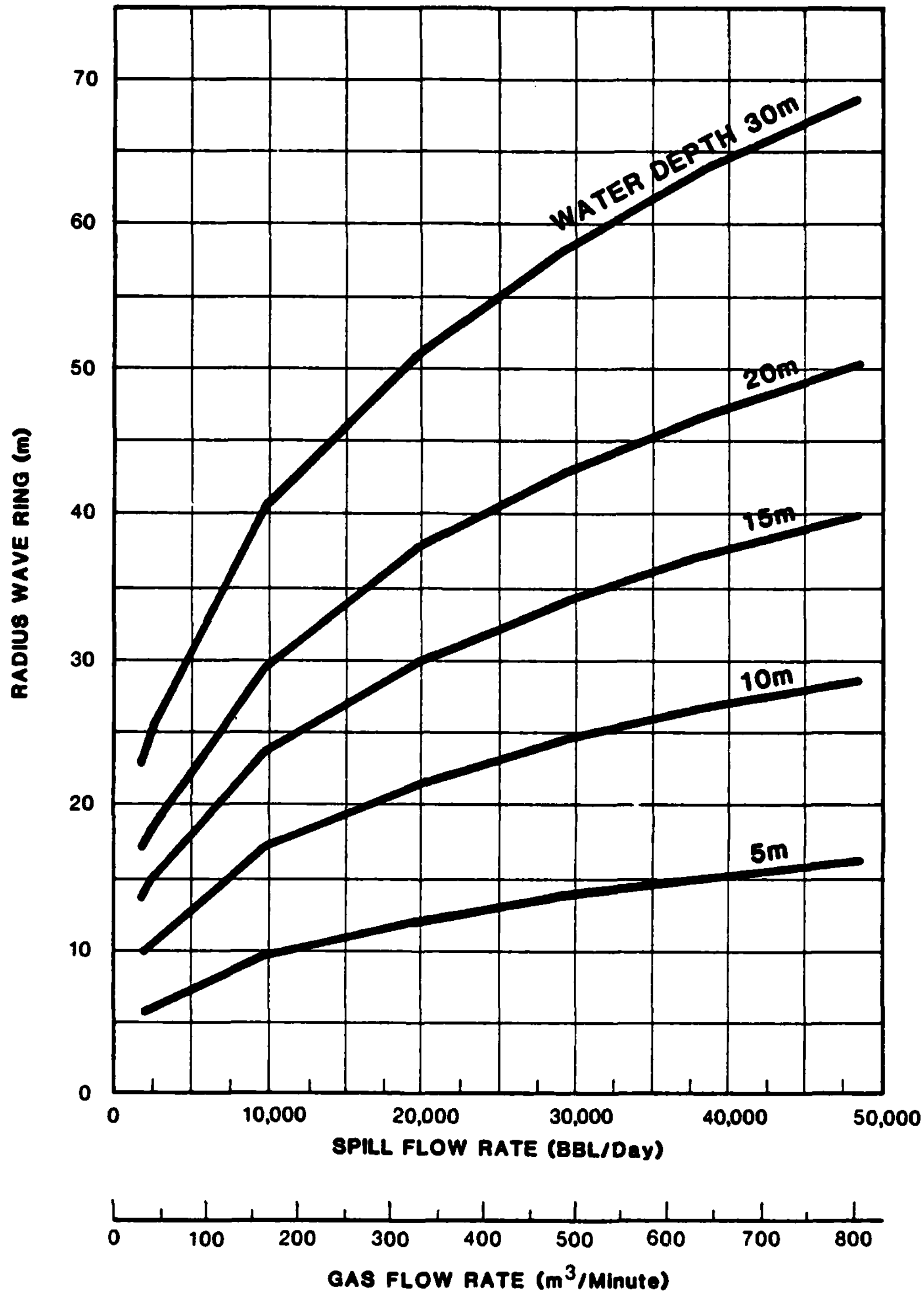

FIGURE 3.6.2 RADIUS OF WAVE RING AS A FUNCTION OF WATER DEPTH AND GAS FLOW/SPILL FLOW RATE. (Assumes gas flow rate to spill flow rate of 150/1 by volume.)

frozen into the ice as a surface layer. If surface conditions are calm, the spill could freeze in as pure oil, but if the winds are high, there is likely to be snow drifting onto the surface forming a snow-oil mixture (35).

In spring and summer a very light crude would form thin surface pools of oil about 2.5 mm thick on water in leads (35). (Arctic diesel could be expected to behave in about the same way.) Pooling of these very light products is expected because of the confining effect of the leads. Heating in the summer would tend to make the oil flow out of the pools, but it would still tend to remain concentrated downwind against the edge of the ice. If the temperature of the water remained around 0°C, a heavier crude, like Prudhoe Bay crude, would have a thickness of about 5 mm.

Lewis develops his spill behavior hypothesis with a blowout under ice scenario that occurs in 23 m of water in March. The standard 2500 bbl per day blowout would have a gas flow of 41 m^3/minute. (If both oil volume and gas volume were shown in cubic meters, the gas to oil ratio would be 150:1.) Figure 3.6.2 shows that this would result in a wave ring radius of about 20 m. The plume would rise at a velocity of about 1 m/sec and the radial surface current at the wave ring radius would be about 0.5 m/sec. The gas would collect at the ice/water interface and also would escape from the drilling hole. At first, most of the oil rising to the surface would move out under a gas layer to a wave ring and be retained by hydrodynamic forces in a layer about 8 cm thick at the leading edge (35). Some of the oil would rise in a pool in the drill hole, and when the thickness of the oil exceeded half the thickness of the ice, it would also flow out over the snow surface. Refer back to Figure 3.6.3, which shows a sketch of how it is postulated that this would occur.

Gas would cause stress in the ice, which would finally rupture. The ice would crack and break at a weak point, but because of the highly variable nature of the ice structure, the way in which this would occur cannot be predicted. Once this happens, the oil and gas will continue to contact the underside of the ice in some places, but it will also come up through the rupture in the ice and begin to flow over the snow on the upper surface of the sea ice.

The blowout would also cause a temperature change under the ice as a result of mixing in the water column from top to bottom (35). Ice would be melted at a rate of 22 cm per day for each degree centigrade of temperature increase. For this scenario a melting rate of about 2 cm per day would be considered as a realistic figure. As melting continues, the oil would remain in the melt dome rather than move out to the wave ring radius. The ice will continue to become thinner until the heat input from the water is balanced by the heat loss to the air. Open water may be seen in the hole on warm days, but ice may grow back into the hole on cold days and reach a thickness of 10 cm before it is removed again.

Frazil ice will form at the oil/water interface in cold weather. These ice particles would be carried out to the wave ring radius where they could double the ice thickness. Figure 3.6.3 shows how this is expected to happen. This growth of ice would change the circulation pattern of the blowout.

Beaufort Sea Field Test. During the winter of 1979-1980 Dome Petroleum Ltd. of Calgary, Alberta

conducted large scale field test to determine the behavior of oil from a blowout under ice (37). This experiment provides the best estimate to date on what would happen during a winter blowout.

The tests were performed 8 km offshore in the Canadian Beaufort Sea under fast ice in about 20 m. of water. An appropriate test apparatus was set up to discharge 19 m3 (120 bbl) of Prudhoe Bay crude at a rate of 2500 bbl per day along with gas (air) at a ratio of 140:1. (There is no point in using real gas in tests because there are no important differences in properties in terms of spill behavior.) To compare seasonal differences in results, discharges were made in December, April, and May.

The "blowout" was a discharge from an orifice on the sea floor surrounded by an elaborate array of devices to observe and measure the results. As the tests began, the oil was observed to break into droplets as the oil/gas mixture left the pipe. The gas flow set up a current around the pipe and drew up some silt from the sea floor. As the gas jet carried the oil and entrained sediments toward the surface, the sediment settled out of the plume and the oil continued to rise because of buoyancy. When the jet stream was within 7 m of the ice it began to spread out radially in turbulent eddies. These eddies decayed into laminar outward flow within a distance of 15 to 20 m. The gas reached the underside of the ice quickly, but the oil came up more slowly, struck the underside of the ice and collected in gas pockets. The sediment that remained in the mixture rained out of the plume. No distinct wave ring was noted, but at about 15 to 20 m from the center of the discharge the water entrained by the gas began to flow down from the surface, possible because of higher density. A slight inward current was noted at 45 m from the discharge center.

The gas quickly collected in pockets under the ice, and then flowed uphill following the normal under-ice contours until it reached an equilibrium point. During a preliminary run that only used gas, a dome of ice 65 cm thick and 50 m wide was lifted up 1 m before it cracked and vented off the gas.

The upward velocity of the oil particles was observed to be related to their size. The small droplets rose slowly and were carried by currents 350 m from the plume centerline. Particle size was observed to decrease significantly with increasing distance from the center of the discharge. Ninety percent of the oil contacted the ice within 50 m of the center of the discharge.

During the December release, 80% of the gas vented through auger holes in the ice (drilled as part of an ice coring program) carried water and more than 3 barrels of oil with it. The oil and water pooled on the surface and quickly froze. This venting had no effect on the areal distribution of the oil compared to later discharges, leading to the conclusion that the size of the contaminated area is controlled by the flow of gas and oil in the water column rather than a surface phenomenon relating to the presence of an ice cover that prevents gas from venting.

During the December tests the under side of the ice was smooth and most of the oil was observed in particles with very few pockets of oil and gas. On the other hand, in April and May the ice was wavy and a large quantity of oil and gas was collected in pockets. Most of the oil was carried up and collected on the underside of the ice within a 50 m radius of a point directly over the discharge point. Only a

small percentage of the oil was carried away by currents.

Spill behavior from an undersea blowout may be somewhat different if it occurs below moving ice. The considerations here are whether the ice will be ruptured by the rising oil and gas and whether the moving ice will transport the spilled oil.

In a study performed for the Outer Continental Shelf Environmental Assessment Office (OCSEAP), Thomas includes calculations showing that gas and oil rising from an undersea blowout would probably be as likely to break slow-moving first year ice as stationary first year ice (25). If, however, the ice is moving at a rate of several kilometers per day, it is possible that the ice would not be broken. The result, then, would be that the spilled oil may be transported great distances from the scene of the spill and released later either when the ice develops cracks or at break-up. If the ice is moving rapidly, a considerable area under the ice could be oiled so that the spill would be spreading as a result of the movement of the ice as well as a result of the hydrostatic force of the accumulated oil.

3.6.3 Surface Blowout

In order to describe spill behavior for all possible situations in the Arctic, it is necessary to also consider the case of a surface blowout. There are no known records of surface blowouts in the Arctic, or even tests simulating surface blowouts. As a result, the assessment of spill behavior for a surface blowout is taken from an engineering analysis developed in a study for the EPA (38).

The study used to develop the surface blowout analysis involves a scenario of a blowout that occurs during February on the North Slope of Alaska about 60 miles southeast of Barrow along the Meade River. Although these conditions are not precisely the same as may be expected in the coastal environment, they are close enough to be used for general planning and illustration.

The scenario assumes a release of crude oil at a rate of about 5,000 barrels per day for a period of about three weeks. After three weeks the well pressure finally drops and the blowout stops. As the spill begins, the crude oil is assumed to be blown out of a high pressure well with high gas content. The spill rate is characteristic of a moderate sized blowout judged to be typical for an average sized petroleum deposit. The purpose of the engineering analysis is to develop a description of the distribution of the oil at the spill site at the time the blowout is secured. The analysis begins by calculating the height of the oil droplets in the plume.

Much of the oil released from a high pressure well will emerge in the form of a mist or spray. After the oil particles reach their maximum height above the well, they begin to feel the effect of the wind and are carried away. The height of the geyser is a function of the reservoir pressure and the exit pressure. Using a typical subsurface well pressure of 845 kg/cm^2 (12,000 psi) and a ground level oil exit pressure of 70 kg/cm^2 (1,000 psi), the velocity of the oil at ground level was calculated to be 26.6 m/s (87.3 ft/s). Using a total energy exchange and assuming no additional energy losses, the geyser attains a height of 34.4 meters (112.9 ft). with the oil having zero vertical velocity at this point.

The horizontal dispersion of the oil droplets is a function of the rate of particle descent. Large drops will fall quickly, landing close to the source. Small drops

can reach maximum descent velocity before hitting the ground and are therefore carried farther by the wind. In calculating the horizontal distance that the oil travels before striking the ground, the system can be viewed as a point source of oil located at the top of the geyser in a uniform wind. Initially, all droplets will undergo a constant acceleration during the fall from the geyser, with smaller droplets reaching a terminal fall velocity before hitting the ground.

Figure 3.6.4 shows a plot of the equation that describes this movement. Based on the Stokes flow assumption, the smallest droplet of oil that hits the ground without reaching terminal velocity has a particle radius of 0.25 mm. Particles having larger radii will return to the ground in a shorter distance.

Weather records for the area show that in winter, winds blow from the sector between NE and SE 50% of the time. Using these average conditions as an example, a 90° wedge between NW and SW would contain 50% of the oil spilled and the remaining area would be covered by the other 50% of the oil.

The average quantitiy of oil spilled in these areas depends on the drop size distribution of the airborne blowout particles. Lacking better information, we assumed the droplet size distribution to be similar to one detemined by Topham for an underwater blowout (34). Since this blowout is in air, the drop sizes were assumed to be half as large. Using Topham's distribution with drops half as large, we assumed that 30% of the particles had a radius less than 0.5 mm, 40% were equal to 0.5 mm, 20% were 1 mm, and 10% were greater than 1 mm. Referring to Figure 3.6.4, a wind speed of 15 knots will carry a drop of radius 0.05 mm out to 928 m from the well head; a drop of radius of 0.12 mm will land about 152 m from the well; and all droplets greater than 0.2 mm in radius will fall on the drill pad. In this case the drill pad is assumed to have the area of a circle with a radius of 61 m, which is the smallest circle in Figure 3.6.5.

Figure 3.6.4 shows that for 10 kts of wind, which is closer to the average for each sector, the maximum distance that fine particles are transported is much less than for 15 kts. For the larger particles, the distance travelled is about the same. Since the highest frequency of particle size is assumed to be 0.5 mm, one may conclude that the pattern of heavy deposits of oil will not be changed much by wind, but that in very high winds, the finest particles may be transported a considerable distance.

Figure 3.6.5 shows the average thickness of oil in each region around the well after 20 days. The oil, of course, will not remain in these thicknesses; it will flow, while it is fluid, to lower ground and into the sand and gravel of the drilling pad (assuming the drilling has been done from a gravel island). Most of the oil estimated to fall on the drill pad downwind from the well will fall or flow into the reserve pit which is always constructed in the predominantly downwind area. Because the pour point of Prudhoe Bay crude is about -10°C, the spilled oil can be expected to become quite stiff in two or three hours in the winter. Lighter oil particles carried beyond the drill pad boundaries are expected to harden during their fall and appear as brown "sleet" as they strike the ground. The smallest of these will continue to be carried by the wind with blowing snow.

<u>The preceding spill behavior model must be considered only as</u>

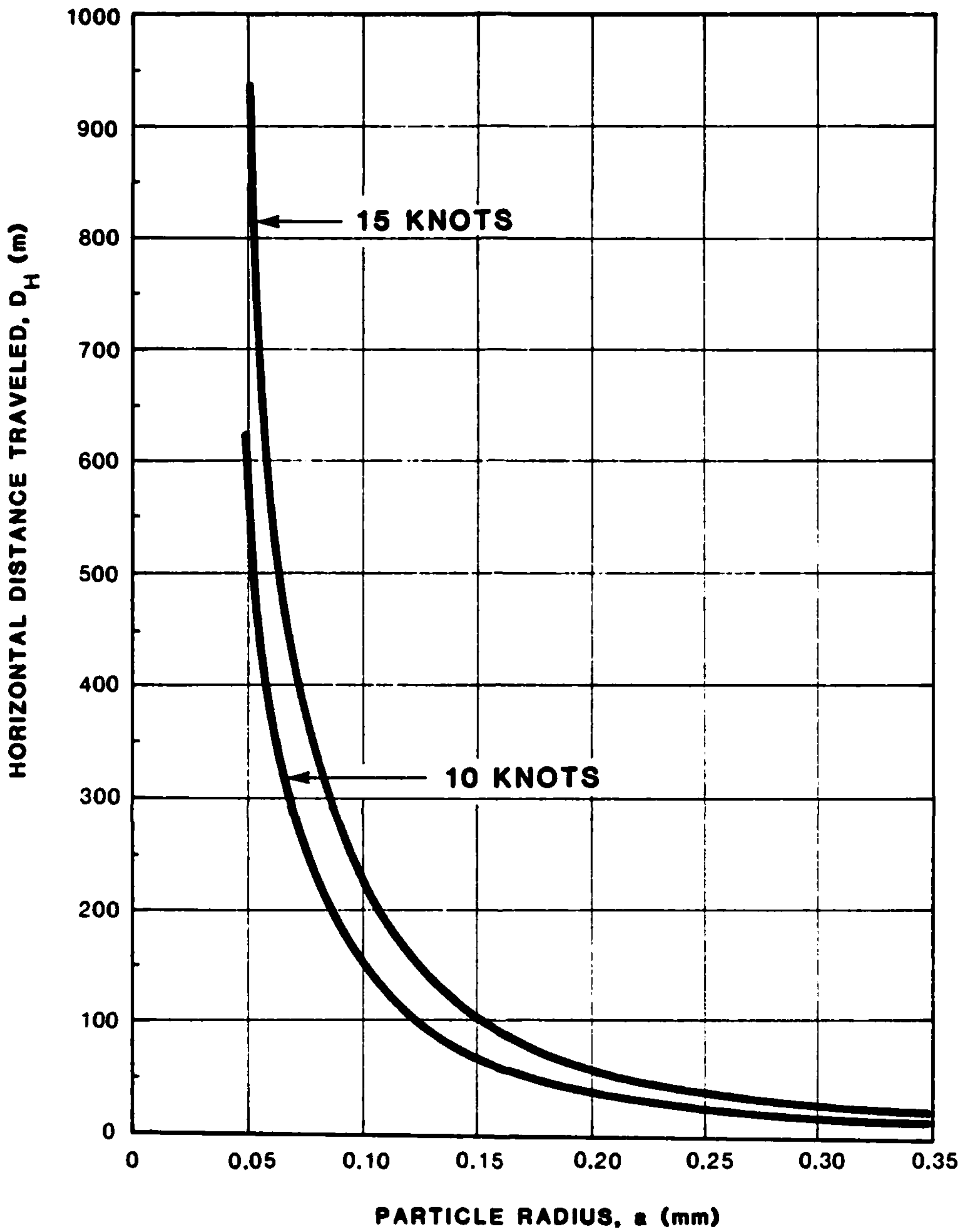

FIGURE 3.6.4 OIL PARTICLE RADIUS VERSUS HORIZONTAL DISTANCE (38)

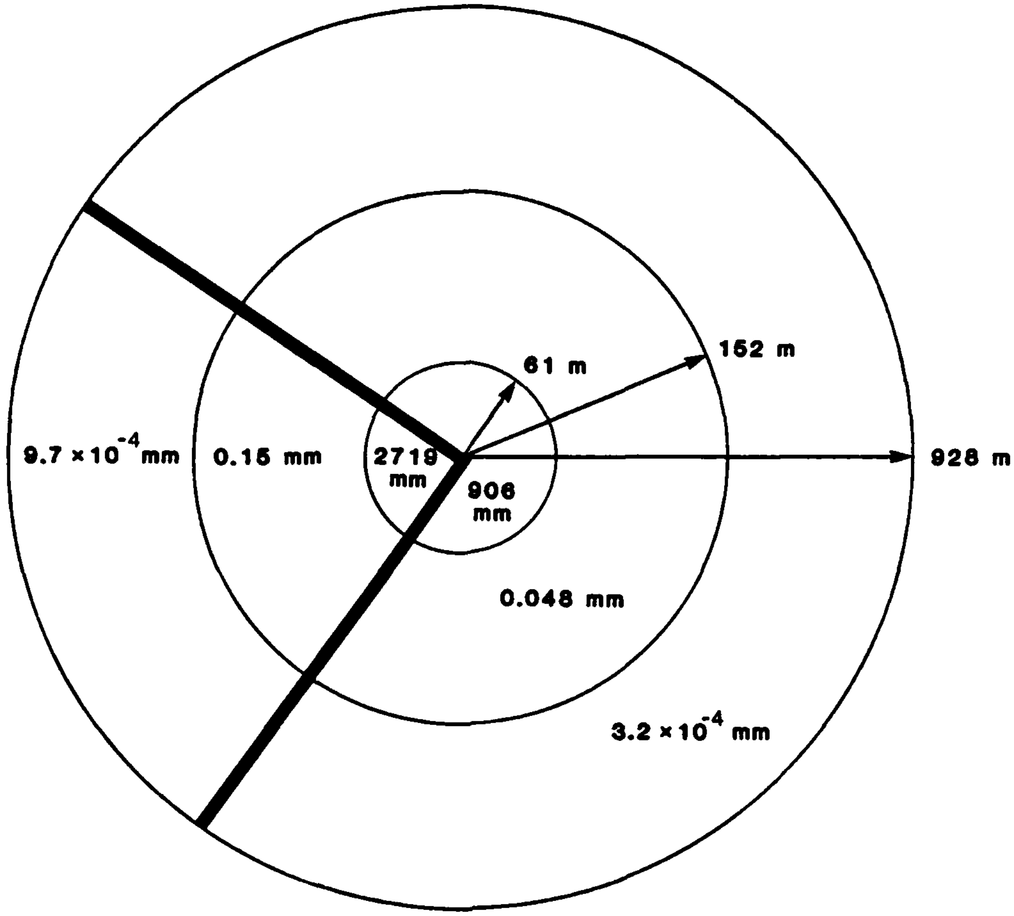

FIGURE 3.6.5 ADVERAGE OIL THICKNESS AROUND A BLOWOUT AFTER 20 DAYS (38)

<u>a best estimate of what might occur in the case of a blowout on the North Slope</u>. The assumption of the distribution of particle size is the weakest part of the analysis. More information is needed concerning this distribution in order to have greater confidence in predicting the way in which the oil will be distributed on the ground in the spill area.

There are also other ways in which the particles from a surface blowout may be distributed. Operators in the field have reported observing blowout conditions in which the heaviest deposits of oil are close to the well, similar to the situation we projected for this scenario. Other observers report blowouts in which virtually no oil falls within a radius of about 150 m of the well. That is, the heaviest deposits form an annulus around the well rather than a thick deposit at the well site. That is rather the inverse of the situation described in this scenario. It must be sufficient to say now that there are likely to be a number of other ways in which the particles

could be distributed around the well in a surface blowout. The preceeding discussion describes a hypothetical surface blowout situation. A number of other surface distribution patterns are also possible depending on the characteristics of the event.

3.7 Migration of Oil in Ice

Studies of the migration of oil in ice are quite diverse because they cover several ice forms and seasons of the year. In order to organize these results, the discussion of migration of oil in ice has been divided into several sections according to season and ice type. That is, the sections describe oil migration in (1) fall, (2) winter, (3) spring, and in (4) deformed ice.

Most of the research on oil migration in ice has been concerned with the active ice seasons, fall and spring. In winter, oil that has been encapsulated in ice is almost dormant. There is some upward migration in brine channels or cracks in ice, but the formation of new ice under the oil is generally the only thing that happens in winter. There has been some work done to plot the upward movement of encapsulated oil in the winter, but not much.

By far, most laboratory and field studies of oil migration have been directed to oil encapsulation in growing ice in the fall and the release of oil from the ice in spring. As a result, looking at oil migration in ice according to season helps to separate the kinds of studies that have been done and the kinds of behavior that is reported.

The seasonal movement of oil in ice can generally be classified as "vertical migration", but this is not true in every case. When the ice is forming in the fall oil may spread over the ice as it is forming or become frozen into the space between pieces of ice. Also, following the rapid vertical migration of oil up through ice in spring, the oil pools on ice, runs down off ice into leads or holes in the ice caused by ablation, and mixes with ice pieces and slush as the ice is deteriorating. Each of these special behavior patterns will be discussed along with the associated seasonal patterns.

Oil may also move into various kinds of ice formations and exibit a behavior pattern that is not seasonal. These situations include oil being incorporated into rafted ice, unconsolidated pressure ridges, rubble piles, cracks in ice, and leads. These behavior patterns can occur in any season and are covered last.

3.7.1 Fall

Only ten years ago Hoult performed the first laboratory studies at M.I.T. to determine oil spill behavior in a growing ice field. The experiments developed some of the basic relationships concerning spill behavior in ice. For example, they showed that there is negligible entrapment of the oil in the under-ice brine matrix (1). But more important, the laboratory tests showed that the ice does not grow up through the oil. Instead, the oil is neatly encapsulated as more clear ice continues to form under it. Further, it was determined that in the absence of currents under ice, large amounts of oil could be entrapped in a lens without being disturbed.

The laboratory studies also provided data that were later confirmed in the field. For example, the laboratory studies noted that the thermal conductivity of oil is about 1/16 that of sea ice. As a result, oil under ice insulates the sea water from the cold temperatures above, and therefore sea ice grows more slowly under the oil than elsewhere

(1). The laboratory experiments also found that ice growing below an oil lens increases the pressure on the oil so that when a core is drilled to the lens, the oil may gush up through the hole until it achieves an equilibrium position at the oil/water interface.

These discoveries were basic to the study of the behavior of oil spilled in an ice environment and provided a starting point for more detailed field work that was to follow.

During the winter of 1974/1975, NORCOR performed field tests for Environment Canada in Balaena Bay near Cape Parry, NWT, in the Canadian Beaufort Sea (21). These tests were the first major field experiments to determine the behavior of oil in ice and remain as probably the most important work that has been done to date.

To study the movement of oil up through ice, two types of crude oil were injected under the ice at various stages of growth between October 1974 and May 1975 (21). The initial spreading and entrainment of the oil was recorded by divers and a video system, and records of the movement of the oil up through the ice were made throughout the period of the tests.

The field experiments show that new ice forms under the oil and encapsulation begins as soon as the temperature of the oil under the ice is close to that of the water. As in the laboratory tests, it was found that the thermal conductivity of the crude oil is about 1/15 that of ice, which makes it an insulator. As a result, the temperature of the ice above the pooled oil drops causing sub-freezing temperatures around the edge of the pool of oil. This results in the formation of a lip of ice around the edge of the pooled oil (21).

Figure 3.7.1 shows a sketch of how this occurs. The "depressed gradient" and the "initial gradient" refer to the relative level of the ice temperature before and after the oil pool formed under the ice. The figure shows that the oil serves as an insulator, so that the cold air depresses the temperature of the ice above the oil. This lower temperature covers enough of an area that it results in the formation of an ice lip around the edge of the pool of oil.

The ice lip is an important feature of the encapsulation process because once it is formed, additional horizontal movement of the oil becomes unlikely. In the depth of winter the ice lip can be expected to form in several hours and in every case within one day.

The time required for ice to encapsulate the entire pool of oil is a function of the thermal gradient of the ice and the thickness of the oil. Although an exact relationship has not been developed, the results of the Balaena Bay tests permit some estimates to be made based on characteristic seasonal ice growth. Thus the time to encapsulate oil in ice is estimated to be:

- Late fall - 5 days
- Deep winter - 7 days
- Spring - 10 days

Recently researchers have found that the time required for encapsulation depends on the ice thickness and the air temperature (39). If the ice is relatively thin (about 60 cm) and the air temperature is very low, encapsulation may occur in only two days.

Encapsulated oil changes the character of the ice both above and below the trapped oil. Tests show

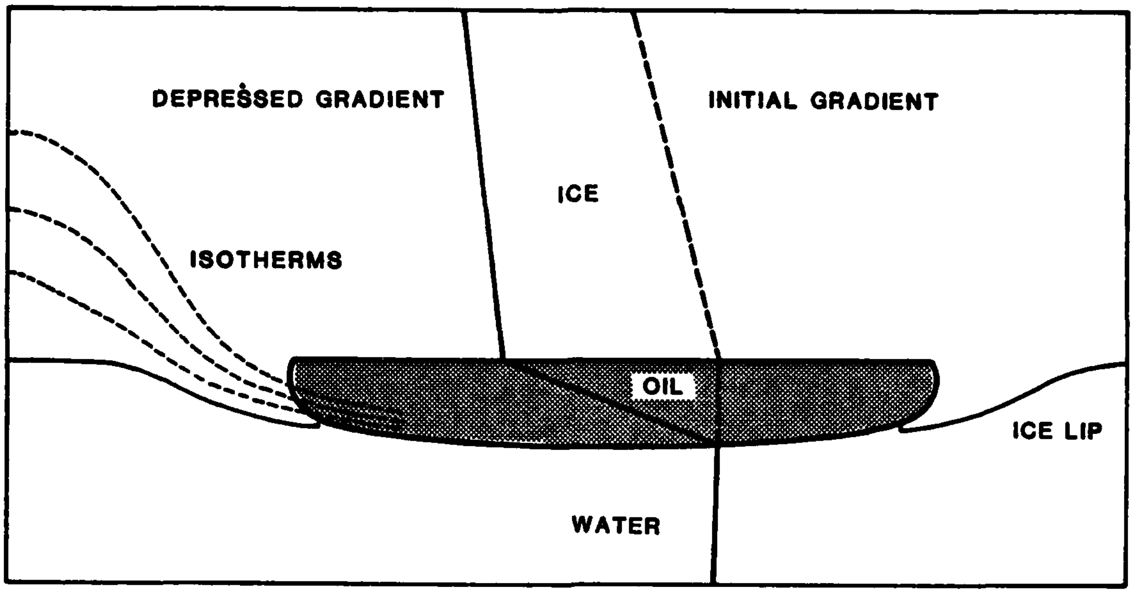

FIGURE 3.7.1 OIL LENS FORMATION (21)

that ice salinity increases immediately above the oil lens. This occurs because the oil lens provides a barrier to the normal downward flow of the brine, which therefore accumulates above the oil.

The salinity of the ice forming below the oil lens was found to be lower than normal. This is because ice grows relatively slowly under the oil, and slow growth traps less brine. Salinity is also low because the new ice is isolated from the brine accumulations above the oil.

The new ice growing under the oil was found to be very smooth and conformed to the underside of the oil lens (21). The surface of the ice appeared to be polished and did not contain large brine channels or crystals typical of uncontaminated ice at that depth. Although there were a few flecks of oil in the ice below the lens, they did not penetrate more than a few millimeters so that the ice below the lens was basically clear.

Above the oil lens the situation was far different. Within a matter of a few days the oil had penetrated several centimeters up into the loose skeletal layer normally present on the underside of sea ice. The interface above the lens was very rough and irregular and individual crystals and brine channels could be easily identified. The ice above the lens tended to be saturated with oil.

The way that oil migrates up through ice is a function of the way in which sea ice grows. In columnar sea ice, the bottom 10 to 40 mm is a skeletal layer. This is porous ice that has a high capacity to absorb oil (40). Harder, columnar ice occurs just above the skeletal layer. Because sea water tries to freeze "fresh", the brine from the sea water is isolated in nearly vertical channels during freezing. The brine gradually works its way down through the ice, slowly at first when the channels may be

only 1 mm in diameter, then rapidly in spring when the channels may grow to 10 mm in diameter as the ice is warmed by the sun. Because of the downward brine movement over the year, fall and winter ice has a high surface salinity but in spring the surface salinity approaches zero.

During the Balaena Bay tests, Martin observed that oil released under ice in October saturated 10 to 20 mm of the skeletal layer at first and then continued to move up 70 to 80 mm through small brine channels (40). While this occurred, an ice cap 10 mm thick grew under the oil lens. This cap was nearly fresh because the insulation of the oil lens caused the ice below the lens to grow slowly, and when ice grows slowly it is nearly salt free.

The laboratory discovery that ice growth puts pressure on the oil was also confirmed in the field at Balaena Bay. When a core was drilled to the lens, the oil flowed up through the hole. In one case oil under pressure even jetted 30 cm above the hole.

Other kinds of oil/ice interactions occur in early fall that do not follow the classical vertical migration patterns.

Consider, for example, the extreme case of spill behavior when oil is floating on open water at a time ice is about to form. In an experiment performed at Balaena Bay, ice formed under the floating oil and there were no signs of oil having penetrated down into the ice (21). The ice grew completely under the oil and resembled a natural ice sheet. The 15 to 20 cm of snow above the slick was saturated with oil, but the snow above this level was not contaminated.

Spill behavior as ice just begins to form is only slightly different. Newly forming ice consists of a highly porous layer of ice crystals. Oil spilled under this formation will quickly rise to the surface (25). Within a few days, the ice will solidify and trap the oil on the surface. Snow falling on this surface may melt either as a result of a temperature change or because of a reduction of albedo caused by the surface oil. The result will be a surface oil lens or an ice/oil/ice sandwich.

Oil surfacing in open leads in fall, or later in the year, is likely to behave in a similar manner. It can be expected to surface even if some ice is present, then grow into a surface lens or sandwich as discussed before.

3.7.2 Vertical Migration in Winter

The migration of oil up through ice is mostly a function of the condition of the ice and to a lesser extent the physical properties of the oil (21). In winter when the ice is cold and growing rapidly, the ice is nearly solid except for the lower skeletal layer. Even though the oil is less dense than the ice, the upward movement is minimal because there are no passages for it to penetrate.

In the tests performed at Balaena Bay, the ice grew at an average rate of about one centimeter per day during the late fall and early winter. During this time the temperature structure of the ice changed, but the configuration of the oil at the ice/oil interface remained about the same. By mid-February warmer temperatures released the brine that was blocking the channels, and the oil began to migrate upward as the channels cleared. At this time the brine channels were found to be about 1 mm in diameter.

Because test oil was released under the ice periodically over the winter, oil lenses were located at

a variety of depths from the surface of the ice at different test sites. Oil properties and behavior did not change as the oil changed its relative position in the ice sheet (21). The early discharges that were close to the surface by spring exhibited similar behavior to those that were near the bottom of the ice sheet.

During March and April the brine channel network continued to develop and the oil slowly moved up through the ice. The brine channels grew from their original position near the lens to about 10 to 15 cm from the surface of the ice. They also increased in size to about 4 mm in diameter and became interconnected with smaller feeder channels. By late spring the ice surface contained a layer of frazil ice and therefore the brine network could not be identified. This surface layer would also quickly refreeze in response to short term changes in air temperature.

Most of the research into oil migration in ice has been done in spring and fall when the movement is the greatest. In one test, however, Nelson and Allen examined the oil lens in March rather than later in spring when the ice was melting (41). This test found that upward migration occurred in winter when the ice sheet was insulated by abnormally deep drifts of snow. In this case the snow was from 0.5 to 1 m thick. The snow insulated the ice from low air temperatures, with the result that the ice was warmed by the sea to a temperature close to what would be expected in spring. Based on this observation, the study concluded that vertical oil migration can be induced in first year sea ice by adding surface insulation to the ice.

This study also found that diesel fuel migrated up much more readily than Prudhoe Bay crude. Water-in-oil emulsions had also been deposited under the ice and it was found that they did not migrate up at all. The brine channels during these tests were reported to vary in diameter from 1 to 20 mm (41).

3.7.3 <u>Vertical Migration In Spring</u>

The phenomena of oil migration up in ice cannot be separated precisely into phases that occur in winter and phases that occur in spring. The process begins as soon as the oil enters the environment and culminates in the spring. There is some overlap, and this section deals with the process that begins in winter (or earlier) and is completed in spring.

There are two competing mechanisms by which oil moves to the surface in the spring: one is the process in which the ice sheet ablates down to where an oil lens is sandwiched in the ice sheet. The second mechanism is the process of the oil migrating to the surface in brine channels (37). Oil deposited under ice in fall and early winter is close to the surface by spring and therefore is likely to be released by ablation. Discharges in late winter and early spring that are a considerable distance from the surface can be expected to be released by vertical movement in brine channels.

As ice freezes, 80% of the brine is rejected downward through the ice and the remainder is trapped in pockets (21). Once the snow is clear of the surface of the ice, the brine channels become the center for melting inside the ice. Channel walls can melt at a lower temperature than the surrounding ice because of the high salt concentration in the brine (35). (The salinity of the brine may be twice that of sea water.) Once the dense brine is released by melting, it moves down into regions of higher temperature where it can cause further melting

and the brine continues to drain down through the ice. As the channels are cleared, they fill with sea water and the brine holes again become the center for melting. When they become fully developed, the brine channels extend from the surface to the bottom of the ice so that they are able to drain surface melt pools.

The salinity of the brine determines the rate at which brine channels drain (21). High salinity lowers the melting point of frozen brine and causes brine channels to open earlier than normal. As air temperatures rise, however, snow on the ice surface melts and runs down into the brine channels where it reduces salinity and permits freezing at a higher temperature (42). This slows the process of brine drainage periodically, but only briefly.

The significance of brine channel development to oil spill behavior is that these channels provide the path for oil trapped under ice or encapsulated in ice to move to the surface. The upward movement is not continuous, however. The vertical migration of the oil is stopped periodically by fresh water from the surface running down into the brine channels and freezing. Occasional colder temperatures increase the viscosity of the oil and temporarily slow or stop the vertical migration of the oil. But in spite of these delays, the upward movement continues until all the oil has surfaced.

The process of oil moving up through brine channels has been observed and documented in the field (21). During the tests performed at Balaena Bay, the ice sheet began to warm in mid-February and the effect of this warming was immediately detectable in the oil. As soon as the temperature increased, the brine began to move down leaving channels for the oil to move up. The oil moved up about 16 cm during a week in February.

The brine network continued to develop during March and April and the oil continued to move up in the ice. By this time the brine channels extended from the initial level of the oil lens to within 10 to 15 cm of the surface. The average diameter of the channels had increased to 4 mm and they were connected to smaller feeder channels.

To check the movement of oil in a well developed network of brine channels, a small amount of crude oil was discharged under 1.95 m of ice on 15 May. (The air temperature was -8°C and the ice surface temperature was -3°C.) In just 45 minutes a single drop of oil appeared on the surface (40). Ice core samples taken in the area showed that the ice was filled with oil. The cores also showed the extent of the growth of the brine channels - one was large enough to hold a pencil.

Some additional work has been done to document the rate at which oil rises in the ice. Thomas (25) used the results of the tests at Balaena Bay to show graphically how the oil was found to rise in the ice. Figure 3.7.2 shows that at the slowest estimated release rate, the oil would be 50% surfaced in a little more than 3 weeks after the first appearance of oil and 100% surfaced in about 6 1/2 weeks. At the fastest rate, the oil would be 50% surfaced in a little more than a week after it first appears and 100% surfaced in about 2 1/2 weeks.

Figure 3.7.3 shows the results of a later but similar test that was performed in the Canadian Beaufort Sea (37). This second set of curves is not presented to confuse the reader, but rather to present all of the information that is available. It must also be recognized that the rate of vertical migration of oil

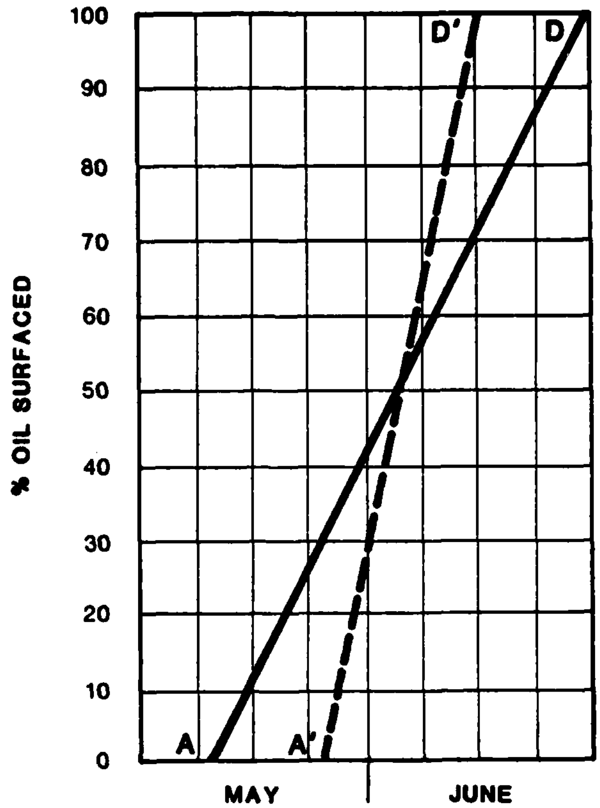

FIGURE 3.7.2 RELEASE RATES OF OIL FROZEN INTO SEA ICE DURING THE EXPERIMENTAL OIL SPILLS AT BALAENA BAY (21,25). Point A indicates when the first oil appeared on the ice surface. Point D indicates when all the ice in the experimental area had melted. Thus line AD is the slowest rate at which oil could have been released. Point A' indicates when oil resumed flowing after a spell of cold weather, and Point D' indicates when the flow of oil was observed to stop. Line A'D' therefore is the fastest rate at which oil could have been released. These curves show that at the slowest estimated release rate, the oil will be 50% surfaced a little more than 3 weeks after the first appearance of oil and 100% surfaced in about 6 ½ weeks.

At the fastest rate, it will be 50% surfaced a little more than a week after it first appears and 100% surfaced in about 2 ½ weeks.

in ice can be expected to vary appreciably place to place and season to season. Figure 3.7.3 shows both the volume of oil that surfaced and the time that was required for it to emerge. The curves also illustrate two other important points. First, the oil surfaced slowly at first but then in a matter of days most of it was exposed. Second, the time that the oil surfaced was dependent on when it was released; the earlier it was released the earlier it appeared. In all, about 80% of the oil from all of the releases surfaced before breakup.

It is also interesting to note that in this more recent Canadian Beaufort Sea test, the slick thickness of oil on pools of water was about 10 mm because of the effects of wind herding. This checks out very well with thicknesses of 5 to 10 mm reported in other field tests and in laboratory experiments.

Considering again the overall results of the Balaena Bay tests, oil that had been discharged during the previous fall was first detected on the surface on 9 May (21). As the oil came up through the ice it just discolored the snow at first, but within 24 hours a pool of oil 1.5 m in diameter had collected. By 12 May 10% of the test area was covered by surfaced oil or darkened snow.

Soon there was 7.5 cm of new snow, but because the oil reduced the albedo of the snow, within 5 days a number of well defined melt pools had developed. These pools increased in size and depth and became interconnected when they reached a common water level. Pools ranged in depth from several centimeters to a maximum of 50 cm. Although the snow was wet, pools did not develop outside the contaminated area.

It is important to note here that wherever the oil came to the surface, it spread laterally on the ice and under the snow. In every case, <u>the color of the snow changed from white to light yellow</u> (40). This is important to spill response crews because it marks the location of the oil. Further, because the oil reduced the albedo of the snow, the snow began to melt and formed a pocket over the oil. <u>Even in snow depths of 30 cm, this color and depth change generally marked the location of the oil</u> (40).

Once melt pools form in the depressions in the snow, oil begins to float on the surface. The increased amount of energy that is absorbed by the oil leads to a rapid growth in the area and depth of the pools (40). It was found that a slick of 10 mm will increase the water temperature 5^{o}C above the ambient temperature.

As melt pools expanded, the oil continued to move up through the ice. The thickness of oil on melt pools increased from 1 mm to 10 mm (21). Oil was thicker when it was herded to the edge of the pools by the wind. Strong winds carried the oil onto the surrounding snow which caused melting in the splash zone and increased the size of the pools.

In time the melt holes increased in size and penetrated the ice so that a high energy vortex could flush the water and oil down through the ice. The oil swept under the ice was deposited within about 2 m of the hole (40). This action tended to be cyclic, roughly corresponding to the rise and fall of the tide. Within 2 days, the size of these holes increased from about 8 cm to about 60 cm in diameter.

<u>It is important to note that once the oil is on the ice surface, it can be expected to be reintroduced</u>

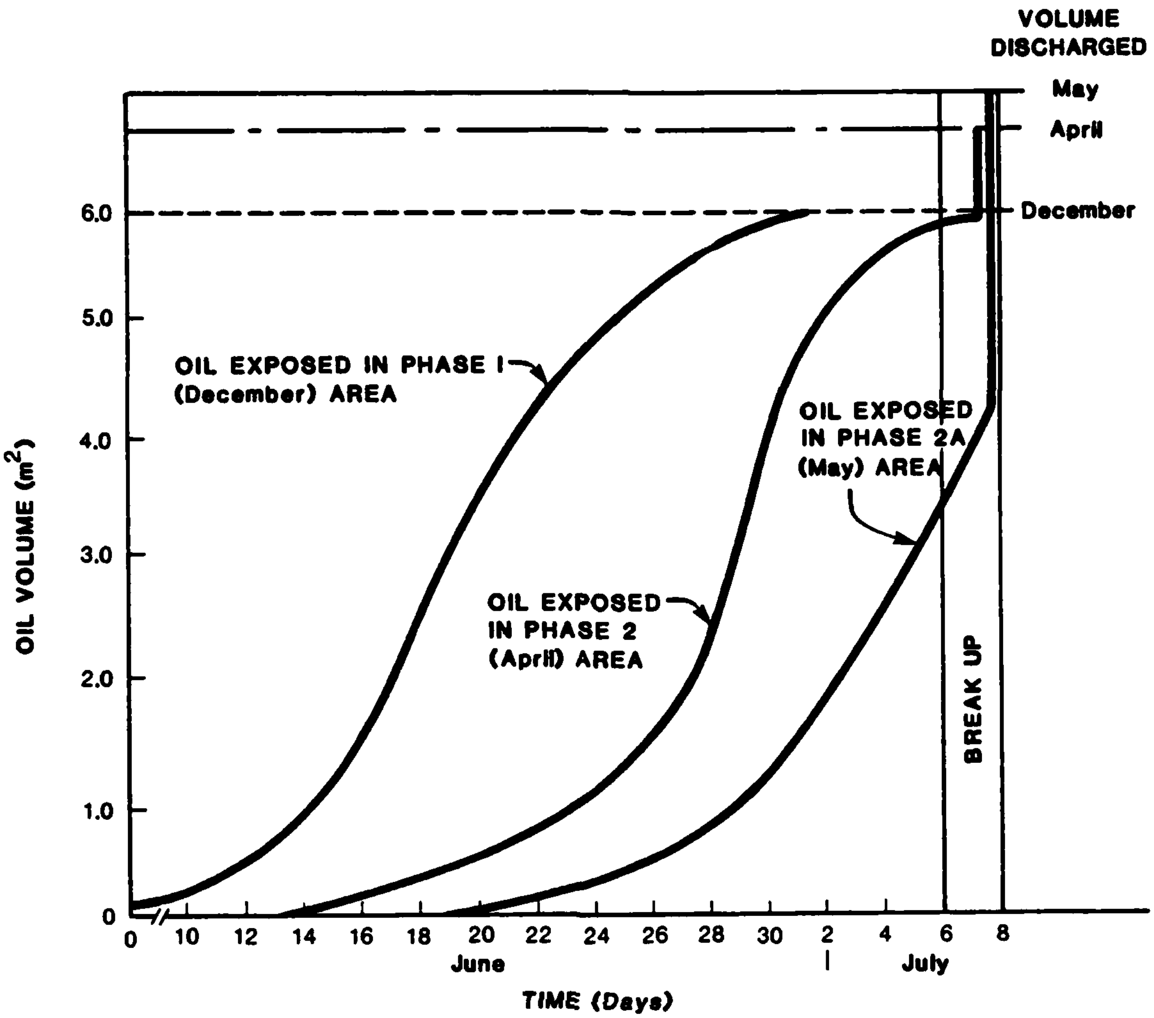

FIGURE 3.7.3 TIMING OF OIL EXPOSURE IN SPRING (36)

into the ocean soon either in a weathered or emulsified form. This will occur either as a result of the ice melting through to the sea surface or by oil flowing off the sides of the ice. If the oil has not been recovered earlier, it will be returned to the sea during break-up. By break-up, things will start to move fast. What had been essentially a dormant spill in the winter ice now becomes an active, fast moving spill situation with oil leaving melt pools in fast moving vortices and streaming off ice into leads. It is important that the OSC anticipate these changes and be ready with appropriate countermeasures.

Oil spill crews always have to worry about whether spilled oil in a high energy environment will emulsify into the typical heavy "chocolate mousse". In the tests at Balaena Bay, having an oil-in-water emulsion was a common event when winds were greater that 15 kts, but these emulsions tended to be unstable and broke down within a day when the winds went down. Chunks of emulsified oil (mousse) were deposited on the snow above the water line and did not break down as readily. These emulsions contained about 40% oil. The Swan Hills (heavy) crude formed more viscous emulsions than the Norman Wells (light) crude (21). It should also be noted

here that in the Canadian Beaufort Sea tests none of the oil coming up through the ice was emulsified (37). This leads one to the conclusion that emulsification is only likely to occur if high energy systems are present after the oil has surfaced.

It is appropriate to note again how the nature of the surface of deteriorating ice affects the behavior of surfaced oil and its tendency to spread. By late May or in June (depending on the season) warming ice becomes porous and less salty (40). The upper part is frazile ice and when it warms it becomes slushy. At the end of May in the Balaena Bay tests, the top 30 mm of the surface was refrozen snow and the 100 mm below was frazile ice. This surface would be a sponge for spilled oil.

This observation checks with the results of the Coast Guard field tests in the Chukchi Sea in July of 1970 (4). In these tests it was found that any oil released on the surface was quickly absorbed into the ice. The fully saturated areas were about 25% oil by volume.

Thus in late spring when the ice is beginning to deteriorate, the OSC can expect surface oil to be absorbed in the thick mass of surface slush. Even though the ice is saturated with oil, the percentage of oil is not high enough to permit effective recovery by most conventional methods. Certainly deployment of most conventional spill response platforms would also be most difficult in this environment. To further complicate recovery, the oil saturating the surface slush is not likely to remain in place long. In a few days it is likely to be streaming out into polynyas and leads. This probably means that once break-up is well advanced and the ice is deteriorating rapidly, any spill response effort would have to wait until there is an open water recovery situation.

The thrust of this discussion is that it would be prudent for the OSC to begin spill response activities as soon as oil spilled in the winter emerges on the surface of the ice in the spring. Soon after pools of oil accummulate on the surface, a spectacular array of melt pond vortices may begin redepositing the oil in the sea. In addition, oil spreading on the surface is likely to be absorbed in a deep layer of slush ice. This oil probably would not be accessible to any response activities until it is finally deposited on the open water.

As a final caveat, the reader is reminded that the surfacing oil reduces the albedo of the area, which then absorbs more heat energy from the sun and accelerates the break-up process. The observers at the Balaena Bay tests report that if the oil had been left in place, the oiled area would probably have been ice free two or three weeks sooner than the undisturbed ice (21). This means that in the oiled areas things will happen fast.

There are two other special circumstances that relate to spring conditions that are described here. The first is the expected behavior of water-in-oil emulsions migrating up through ice in the spring, and the second is the effect rivers have on spill behavior at break-up.

A great many spills in high energy ocean areas have resulted in the formation of a dense, high viscosity water-in-oil emulsion. This emulsion has been very difficult to deal with using any conventional spill response methods. As a result, even so much as a threat of this emulsion forming in an arctic spill has led researchers to perform additional tests to determine the behavior of emulsions in ice.

During the winter of 1981-82 Dome Petroleum tested the behavior of emulsion in ice at their offshore operating area in the Canadian Beaufort Sea (43). Three discharges of oil were made under ice on 20 and 21 March: two of a 60% water-in-oil emulsion and one of a control crude.

When discharged, both the crude and the emulsion broke into discrete globules that floated up against the ice. The emulsion remained static with an irregular, lumpy texture. Within 24 hours new ice crystals were observed forming within the emulsion itself. Within 48 hours both the emulsion and the crude were almost completely incorporated in a thin skin of 2-3 mm of new ice growing under the oil.

Spring observations of the test sites began on 15 June. Ablation had just begun and all the sites were covered with 10 to 20 cm of water. The important discovery in the tests was that the emulsion does not migrate up in brine channels at all. Rather, it surfaces in lumps when there is a large opening in the ice all the way to the surface. With only 3 days remaining until break-up, less than 15% of the emulsion was floating on the surface even though several holes were rotted in the ice all the way down to the emulsion layer. At that same time 50% of the control release of crude had surfaced. At one site large quantities of emulsion remained trapped in rotten ice up to 5 July.

It seemed clear to the observers that the high viscosity of the emulsion slowed the vertical migration through the ice. Apparently it was not possible for significant amounts of emulsion to surface even when a clear passage to the surface was available. <u>The emulsion seems to have appeared on the ice surface by melting its way through the ice sheet en masse</u>.

The ice sheet at the test site reached a maximum thickness of 180 cm. Break-up occurred when the ice was 50 cm thick. Observers reported that the emulsion came up through about 35 cm of ice. The emulsion was visible through the ice when it was about 50 cm thick, which probably permitted the emulsion to be warmed by the sun, increased melting, and enhanced the movement upward.

The consistency of the emulsion at the site was about that of peanut butter. Mats of emulsion were observed to be submerged by rainfall. <u>Ice cores showed that there was no movement of the emulsion up through the brine channels.</u>

The emulsion did not break during its encapsulation in the ice or during its exposure on the surface. The water content of the emulsion dropped from 57% to 47%, but this was about the only change. The conclusion is that if emulsion is present, it will surface very slowly, much later than the unaltered crude. In fact, the ice must be deteriorated to the point that the emulsion can rise vertically in a mat.

The reader must be cautioned here that these tests and this discussion make no assumptions about whether emulsion will form in this environment. In fact, it seems less likely that emulsion would form in an under ice blowout than in an undersea blowout in an area of high energy waves.

Another special consideration for oil spill behavior at break-up involves the effects of river outflows. Oil spilled in the vicinity of river outflows would be rapidly dispersed, both laterally and downward into drain holes (44). The oil would also mix with river sediments and organic materials that could cause it to sink. By late June to early July oil spilled near rivers would have been swept out into open water.

The distribution of the oil might be patchy; much of the oil would be in slicks, but some would be constrained in the ice.

The Colville River floods during the first week in June. The runoff fans out over and under fast ice, which would disperse spilled oil in a fan-like pattern off shore (44). The sediment load of the river would cause some of the oil to settle to the bottom. Dark patches of sediment and oil on the surface of the ice would accelerate melting. The oil could be expected to weather rapidly on the surface of the ice, and the high energy levels of the river could be expected to form water-in-oil emulsion.

The OSC should expect silt flowing out of rivers to cause some sedimentation of spilled oil. Although the amount of oil lost to the spill from sedimentation may be small, the potential impact on the offshore environment could be important.

3.7.4 Spill Behavior in Deformed Ice

Spill behavior in deformed ice has been separated out because it is different from behavior under fast ice or pack ice, and because oil could enter deformed ice in nearly any season.

For example, oil may be incorporated in an unconsolidated pressure ridge or shear ridge (25). This oil could remain in the ridge in an unweathered state over several melt seasons. As a side note, these ridges could also travel great distances and therefore distribute the oil over wide areas.

There are some field test results available that illustrate the behavior of oil in deformed ice. In the Balaena Bay tests in Canada, a crude oil was released under ice adjacent to a small, weathered pressure ridge (42). Most of the oil was trapped in a cavity to a depth of about 10 cm adjacent to the ridge. About six weeks later, the oil came up through the pressure ridge to mark the spill site. (The oil was released 8 April and it surfaced 30 May).

Cores taken through the pressure ridge showed that the spill behavior was sometimes the same as in fast ice and sometimes different. One core showed a small oil lens with thick ice beneath, but some oil had migrated to the surface. Another core showed a larger oil lens with less ice beneath, but the core was oiled vertically 1/3 of the way up, it was clear for 1/3, then oiled again in the top third. One core had a lens 100 mm thick, and after taking the core pure oil flowed from the lens to the surface.

These results show that many different kinds of spill behavior are possible in deformed ice. Oil may flow relatively freely up in and through unconsolidated pressure ridges; however, the behavior in consolidated ridges (i.e., ridges that have water filling and refreezing in the voids), is likely to be much different, sometimes more like the behavior in fast ice.

Spill behavior in deformed ice features was also observed during the spill of #2 fuel oil from a barge in Buzzard's Bay, Massachusetts (17). The spill environment was not like the Arctic, since there was only 30 cm of low salinity ice, but the observations made at Buzzard's Bay can be applied to other spill situations.

Because of the relatively high energy in the area caused by currents, and because the ice was thin, there were many examples of rafted ice in the area. It appears that the currents carried the oil under the

ice until it stopped and collected in the lee of the rafted depressions. The buoyancy of the oil then permitted it to move up to collect in the surface depression caused by the rafting. Figure 3.7.4 shows how this occurred. Some of the pools of oil found in the rafted ice were 10 cm deep and contained 200 to 2,000 gallons of oil. Remember that this Figure shows the behavior of #2 fuel oil. A heavy crude in cold water is not likely to surface as freely.

The oil moving under ice also encountered some unconsolidated hummocks. Figure 3.7.5 shows how the oil is likely to have become incorporated in the hummocks. The oil in the hummocks was much less concentrated than the oil that was found pooled on the rafted ice. There was no flow of oil from a core taken in the deformed ice. The core contained oiled ice, but there was no evidence of the ice retaining liquid oil.

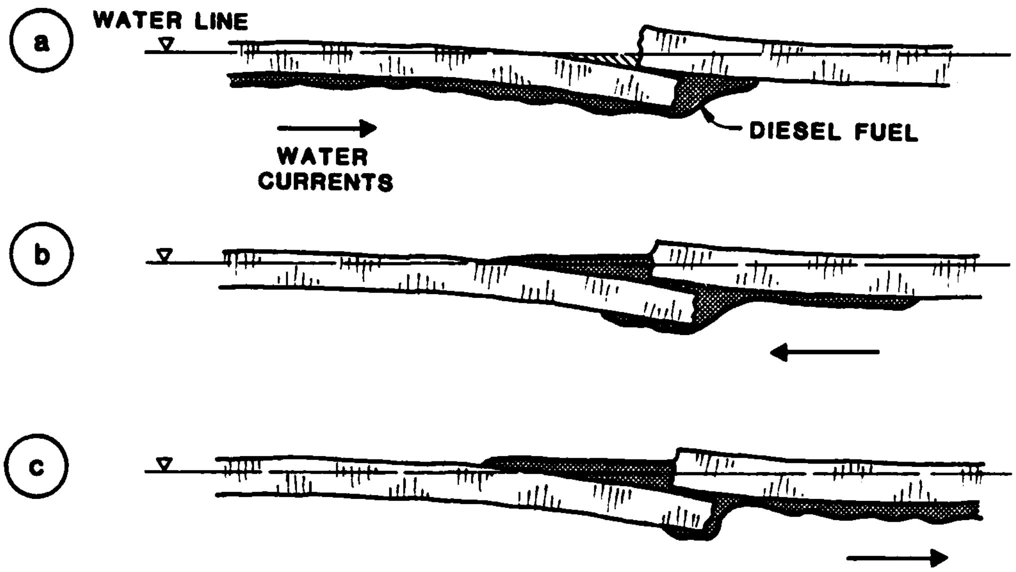

FIGURE 3.7.4 FLOW OF OIL IN RAFTED ICE (17) a) Oil under ice meets rafted ice, b) Current reversal causes filling in rafted ice depression, c) Current reversal sweeps unsheltered oil away.

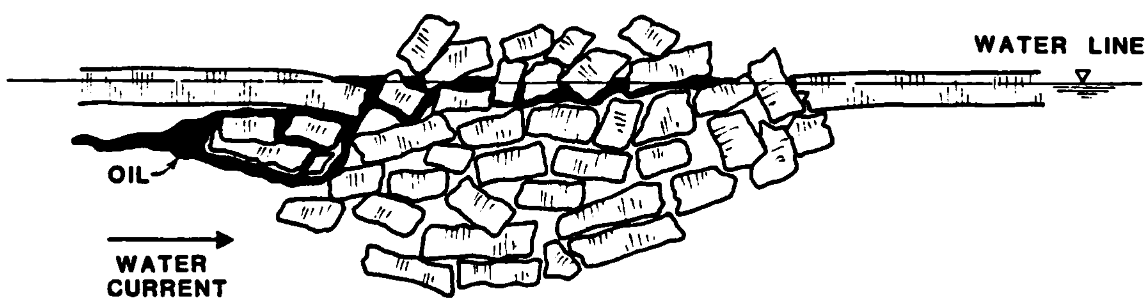

FIGURE 3.7.5 OIL FLOWING INTO CROSS-SECTION OF HUMMOCK (17)

BEHAVIOR REFERENCES

1. Hoult, David P., Oil in the Arctic, Report No. DOT-CG-42913-A, U.S. Coast Guard, Office of Research and Development, Washington, D.C. February 1974.

2. McMinn, T.J., LTJG USCG, Oil Spill Behavior in a Winter Arctic Environment, Offshore Technology Conference, Houston, Texas, 29 April - 2 May 1973.

3. Isakson, J.S., J.M. Storie, J. Vagners, G.A. Erickson, J.F. Kruger, and R.F. Corlett, Comparison of Ecological Impacts of Postulated Oil Spills at Selected Alaskan Locations, U.S. Coast Guard Report No CG-D-155-75, Washington, D.C. Office of Research and Development, June 1975.

4. Glaeser, J.L. LTJG and LCDR George P. Vance, A Study of the Behavior of Oil Spills in the Arctic, U.S. Coast Guard, Office of Research and Development, Report 714108/A/001,002, Washington, D.C., February 1971.

5. Waldman, George A., Ronald A. Johnson, and Peter C. Smith, The Spreading and Transport of Oil Slicks on the Open Ocean in the Presence of Wind, Waves, and Currents, U.S. Coast Guard Report No. CG-D-17-73, Office of Research and Development, Washington, D.C. July 1973.

6. Aravamudan, K., P. Raj, J. Ostlund, E. Newman, and W. Tucker, Break-Up of Oil on Rough Seas - Simplified Models and Step-By-Step Calculations, Report No. CG-D-28-82, U.S. Coast Guard, Office of Research and Development, Washington, D.C. March 1982.

7. Mackay, Donald, Wan Ying Shiu, Khon Hossain, Warren Stiver, Diane McCurdy, and Sally Paterson, Development and Calibration of an Oil Spill Behavior Model, Report No. CG-D-27-83, U. S. Coast Guard Research and Development Center, Groton, Connecticut, September 1982.

8. Contingency Plan of the Alaska Oil Spill Response Body (ABSORB), 1980.

9. Burns, Kathryn A. and John M. Teal, Hydrocarbon Incorporation into the Salt Marsh Ecosystem From the West Falmouth Oil Spill, Report COM-73-10419, prepared for Bureau of Commercial Fisheries, National Science Foundation, November 1971.

10. Boehm, Paul D., Baffin Island Oil Spill Project - Chemistry Component, Volume 2, Environmental Protection Service, Department of the Environment, Edmonton, Alberta, Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of Principal Investigators for the year ending March 1981, Volumne IV: Effects of Contaminants.

11. Petersen, Hanne K., Fate and Effect of Bunker C Oil Spilled by the USNS Potomac in Melville Bay, Greenland, 1977, Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills, Keystone, Colorado, June 1978.

12. Forrester, W.D., Distribution of Suspended Oil Particles Following the Grounding of the Tanker ARROW, Journal of Marine Research, Vol 29, No. 2, 1971.

13. Tebeau, Peter A., Thomas A Meehan, and Steven A. Saepoff, A Laboratory Study of Oil Spreading Under Arctic Conditions, U.S. Coast Guard Research and Development Center, Groton, Connecticut.

14. Free, A.P., J.C. Cox, and L.A. Schultz, Laboratory Studies of Oil Spill Behavior in Broken Ice Fields, U.S. Coast Guard Research and Development Center, Groton, Connecticut, October 1981.

15. Schultz, L.A. Tests of Oil Recovery Devices in Broken Ice Fields, Phase II Final Report, U.S. Coast Guard Office of Research and Development, Washington, D.C. January 1976.

16. Martin, Seelye, Peter Kauffman, and Per Erik Welander, A Laboratory Study of the Dispersion of Crude Oil Within Sea Ice Grown in a Wave Field, Proceedings of the Twenty-Seventh Alaska Science Conference, Fairbanks, Alaska, August 1976.

17. Deslauriers, P.C., S. Martin, B. Morson, and B. Baxter, The Physical and Chemical Behavior of the Bouchard #65 Oil Spill in the Ice Covered Waters of Buzzards Bay, OCSEAP, NOAA, June 1977.

18. McLean, A. Y., The Behavior of Oil Spilled in a Cold Water Environment, Proceedings of the Offshore Technology Conference, Houston, Texas, May 1972.

19. Minister of Transport, Report of the Task Force Operation Oil, (Clean up of the ARROW oil spill in Chedabucto Bay), 1970.

20. C-CORE, An Oilspill in Pack Ice, Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, January 1980.

21. NORCOR Engineering and Research, Limited, The Interaction of Crude Oil With Arctic Sea Ice, Beaufort Sea Technical Report #27, Beaufort Sea Project, Department of the Environment, Victoria, B.C., December 1975.

22. Rosenegger, L.W. Movement of Oil Under Sea Ice, Beaufort Sea Technical Report #28, Beaufort Sea Project, Department of the Environment, Victoria, B.C. December 1975.

23. Barnes, Peter W., Erk Reimnitz, Lawrence J. Toimil, and Harry R. Hill, Fast Ice Thickness and Snow Depth Relationships Related to Oil Entrapment Potential, Prudhoe Bay, Alaska, Fifth International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), The University of Trondheim, Norway, August 1979.

24. Kovacs, Austin, Rexford M. Morey, Donald F. Cundy, and Gary Decoff, Pooling of Oil Under Sea Ice, Proceedings of the Sixth International Conference on Port and Ocean Engineering Under Arctic Conditions, Quebec, Canada, July 1981.

25. Thomas, D.R., Behavior of Oil Spills Under Sea Ice - Prudhoe Bay, Flow Research Report No. 175 appearing in the Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of Principal Investigators for the year ending March 1981, Volume VI: Transport.

26. Cox, J.C., L.A. Schultz, R.P. Johnson, and R.A. Shelsby, The Transport and Behavior of Oil Spilled In and Under Sea Ice, Final Report for Research Unit 568, NOAA, OCSEAP, September 1980.

27. Cox, J.C. and L.A. Schultz, The Transport and Behaviour of Spilled Oil Under Ice, Proceedings of the Third Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1980.

28. Golden, Paul C., LTJG, USCGR, Oil Removal Techniques in an Arctic Environment, MTS Journal V.8., no. 8, January 1974.

29. Mackay, D., M.E. Charles, and C.R. Phillips, The Physical Aspects of Crude Oil Spills on Northern Terrain, Minister of Indian and Northern Affairs, Ottawa, 1975.

30. Ramseier, R.O., G.S. Gantcheff, and K. Colby, Oil spill at Deception Bay, Hudson Strait, Environment Canada Scientific Series Report #29, Ottawa, Canada, 1973.

31. Carstens, T. and E. Sendstad, Oil Spill on the Shore of an Ice-Covered Fjord in Spitsbergen, Proceedings of the Fifth International Conference on Port and Ocean Engineering Under Arctic Conditions (POAC), The University of Trondheim, Norway, August 1979.

32. Nelson, William G. and Alan A. Allen, The Physical Interaction and Cleanup of Crude Oil with Slush and Solid First Year Sea Ice, Proceedings of the Fifth Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1982.

33. Mackay, Donald, Paul J. Leinonen, John C.K. Overall, and Barry R. Wood, The Behavior of Crude Oil Spilled on Snow, ARCTIC, Journal of the Arctic Institute of North America, Volume 28, Number 1, March 1975.

34. Topham, D.R., Hydrodynamics of a Blowout, Beaufort Sea Technical Report #33, Department of the Environment, Victoria, B.C. December 1975.

35. Lewis, E.L. Oil In Sea Ice, Pacific Marine Science Report 76-12, Institute of Ocean Sciences, Sidney, B.C. 1976.

36. Thornton, D.E., The Flow Structure of an Underwater Oil Blowout, SPILL TECHNOLOGY NEWSLETTER, January-February 1978.

37. Buist, I.A., W.M. Pistruzak, and D.F. Dickins, Dome Petroleum's Oil and Gas Undersea Ice Study, SPILL TECHNOLOGY NEWSLETTER, May-June 1981.

38. Schulze, Robert, J.C. Cox, and L.A. Schultz, Oil Spill Behaviour in Remote Inland Environments, Proceedings of the Third Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June, 1980.

39. Personal communication with James Payne, principal investigator for a NOAA, OCSEAP petroleum weathering study, July 1984.

40. Martin, Seelye, The Interaction of Oil With Sea Ice in the Arctic Ocean, BLM/NOAA Contract No. 03-5-022-67, Seattle, Washington, March 1977.

41. Nelson, William G. and Alan A. Allen, Oil Migration and Modification Processes in Solid Sea Ice, Proceedings of the 1981 Oil Spill Conference, March 1981.

42. Martin, Seelye, A Field Study of Brine Drainage And Oil Entrainment in First-Year Sea Ice, Journal of Glaciology, December 1978.

43. Buist, I.A., S.G. Potter, and D.F. Dickins, Fate and Behaviour of Water-in-Oil Emulsions in Ice, Proceedings of the Sixth Arctic Marine Oilspill Program Technical Seminar, Edmonton, Alberta, June 1983.

44. Outer Continental Shelf Environmental Assessment Program, Interim Synthesis Report: Beaufort/Chukchi, Arctic Project Office, August 1978.

4.0 OIL INTERACTION WITH SHORELINE

4.1 Background

Since there is no oil spill experience in the Alaskan Beaufort Sea, prediction of oil interaction with the shoreline must be based on experience in other areas and then related to the Alaskan coastline in terms of similarities or differences in coastline types. This section therefore begins with a description of current experience of the interaction of large spills with a shoreline. Next it describes methods of evaluating coastlines for oil spill impact and retention. Finally, it describes the expected retention capability of the Alaskan Beaufort Sea coastline based on an evaluation of coastline types.

4.2 Current Experience

The spill of the tanker METULA in the Strait of Magellan is one of the the best documented spill events that had a significant impact on a coastline. The impact of the spill on the coastline was recorded at the time of the spill and the area has been re-visited several times over a period of years. It is therefore possible to trace how the spilled products degraded over an extended period of time. Since no spill cleanup was attempted, this can be considered as a baseline case.

On 9 August 1974 the 206,000 ton tanker METULA ran aground in the Strait of Magellan, Chile (1). In a month and a half, 51,000 tons (about 330,000 barrels) of light Arabian crude and 2,000 tons of Bunker C were released and washed up on 80 km (43 nm) of shoreline.

The area where the spill occurred is semi-arid with summer temperatures of 3 to 29°C (37 to 84°F) and winter temperatures of -13 to 9°C (9 to 48°F). Shoreline ice is not common. The area also has extremely high tides that range from 6 to 10 m, currents up to 8 kts, and winds with an average velocity of 27 kts. In 1981, six and a half years after the spill, a survey of the area showed that much of the oil still remained. An abbreviated list of the spill residues that remained in 1981 includes the following:

- o An oiled sediment layer
- o Oil-clumped sand and an oiled sediment pavement
- o Extensive beds of asphalted pavement 20 to 40 m wide and in some places 100 m wide. In the 6.5 year period since the spill, the pavement showed only minor signs of patchy erosion
- o A heavily oiled marsh that showed only minor signs of recovery
- o Buried oiled sediment, now hard asphalt, stranded along 2.5 m of upper berm
- o A zone of asphalted pavement, 90 to 100 m wide along the upper low-tide terrace

This list contains only a sampling of evidence of spill impact that remained after 6.5 years. A survey taken in 1975/76, 1.5 years after the spill, estimated that oil mixed in sand and gravel beaches would remain 2 to 3 years and oil in the marsh would remain about 20 years. After the 1981 survey, the new estimate is that on low energy sand and gravel beaches the oil will remain for 15 years, and where wave action is very limited, the oil will remain more than 30 years. The prediction for a heavily oiled marsh is even worse. "With less than one percent new growth at the site and little evidence of oil weathering, oil may persist for

more than 100 years (1)."

The METULA spill is certainly the extreme case of a large spill that encountered a shoreline, but spills of this magnitude could also occur in the Arctic. Further, the potential for long term spill persistence is even greater because of low wave energy along the shoreline and reduced rates of degradation in low temperatures.

Although there are not many examples of spill impact on a shoreline in an ice environment, the grounding of the ARROW in Chedabucto Bay, Nova Scotia does provide some insights into the problem (2). The paragraphs that follow describe some examples of oil-ice interaction that occurred along the shoreline after the ARROW spill and can be related to likely spill behavior in the Alaskan Beaufort Sea.

Some of the oil trapped in lagoons after the ARROW spill was later covered by ice. In one case these ice covered accumulations of oil were more than 10 cm deep. This encapsulation of oil in ice occurred as a result of low temperatures together with overriding mixtures of ice and water. The over night temperature in Chedabucto Bay dropped to -15°C (5°F). The lagoon froze with a slurry of ice and water freezing over the oil. In places where the oil was resting on ice before it was encapsulated, an ice-oil-ice layer formed with oil sometimes 15 cm thick. The trapped oil did not mix with the ice or continue to weather after it was frozen in. Instead the encapsulated oil looked black and fresh when it was exposed.

Along the open shoreline, thick layers of oil first covered the ice and snow and later the underlying rock and water as melting occurred. Two types of mixtures were deposited in areas where ice was forming as oil came ashore:

o Coarse crystalline ice, unconsolidated and light brown in color. Small oil particles were visible around and in the ice crystals. These formations were 1 to 5% oil.

o Consolidated pieces of ice that contained lumps of oil. This mixture was about 7% oil.

In some places the shoreline was cleaned by bulldozing, but this was stopped because the oil content of the recovered materials was less than 5%.

4.3 Possible Spill Impact

The Final Environmental Impact Statement (EIS) for the Diapir Field Lease Offering provides some additional insights into possible impact along the shoreline in the event of a spill (3).

First the EIS speculates on how much of the shoreline would be affected by an offshore spill. Assuming that the oil deposited on the shoreline is 1 to 10 mm thick, a 1,000 barrel spill would cover 0.016 to 0.16 km^2 and a 10,000 barrel spill would cover 0.16 to 1.6 km^2. This does not seem like a very large area, but on a shoreline a broad area is not likely to be covered. Rather, a strip of shoreline is likely to be covered at the high tide mark. It is therefore useful to re-arrange the estimate of the area covered to help to visualize the length of shoreline that might be affected. If a 2 m wide strip of shoreline were affected, 0.16 km^2 would cover 80 km or 43 nautical miles of beach. Making the same assumption, 1.6 km^2 would affect 800 km or 432 nautical miles of the beach. Thus a 10,000 barrel spill has the potential for affecting a very long strip of shoreline.

The EIS goes on to suggest that the offshore slick is not likely to be continuous. In fact, the slick

is likely to be broken up into small segments by winds, waves, current, and ice. Further, some of the oil may be driven into the water column, absorbed by sediments, trapped by ice, or carried off to sea. In any case, not all of an offshore spill is likely to reach the coastline. The spill may contact the shoreline in several locations or it could be smeared along a single location depending on the nature of winds and longshore current. Because of the number of variables involved, current capability to predict coastal coverage by an oil spill is limited.

The greatest potential for shoreline impact from an offshore spill would come from stranding in a marsh or on delta tidal flats (3). The EIS points out, however, that because the tide range is quite low in the Alaskan Beaufort Sea (about 10 to 30 cm), these areas are only covered by water during storm surges. As a result, if a storm surge does not occur while the spilled oil is offshore, these areas are not likely to be affected.

During the period 1960 to 1977, 12 storm surge events were recorded for the Beaufort-Chukchi coast. This is an average of less than one storm surge per year. This would lead one to believe that the probability of having a storm surge while the oil is in the water is not very large. This conclusion may be justified, however it must be tempered by the fact that the storm surge must occur in open water. Since there is only open water for about two months in the summer, this narrows the window considerably. If there is a spill offshore, there is quite a good chance that a substantial part of it will remain in the water during most of the open water season. If there are 0.7 storm surges per year, then the chance that a storm surge will carry spilled oil into a marsh is much better than even.

The EIS also points out that oil transported ashore during a storm surge would be likely to be stranded at the high water mark in the tidal flats rather than being spread over the entire area. This observation is based on the driftwood lines that occur in these areas.

The persistence of oil on beaches, tidal flats, marshes, and other shoreline types along the Beaufort Coast is difficult to judge (3). Most studies to date rate the persistence of oil on the Beaufort Sea shoreline as high to very high. Section 4.5 contains a description of the rating system and an evaluation of the entire coastline. These ratings reflect not only the retention capability of the substrate, they also reflect the level of effectiveness of natural physical processes to remove the oil. The greatest persistence of spilled oil would occur in marshes, tidal flats, or on low tundra (peat) shores. In these areas, Nummedal (4) estimated that oil incorporated into sediments, organic debris, or into matted vegetation could remain for as long as 10 years and possibly longer. Based on the last visit to the METULA spill mentioned earlier (1), the stranded oil might remain in place for a very long time indeed. Gundlach suggests that even in the more temperate climate of Chile, oil could remain in sheltered marshes for more than 100 years. Low temperatures and a short thaw season are likely to make spill residues even more persistent in the Arctic.

The EIS also suggests that the potential for spill impact to marshes would probably be higher than for tidal flats because the arctic marshes are relatively closed and therefore are more likely to retain oil(3). Also, weathered crudes are less likely to penetrate the ground in the Arctic because the soil is generally frozen and low temperatures make the spill residues highly viscous. The result

would be more surface paving of the coastline and less penetration and covering by sediments.

Some of the oil spill risk is to barrier islands rather than to the mainland. In these cases the potential for damage is less because barrier islands generally have moderate oilspill retention capability and are easier to clean up than mainland shores. Some sections of the coastline, such as Cape Halkett and Konganevik Point, have no barrier island and high to very high potential for retaining oil. In these areas there is a great threat of high spill impact (3).

4.4 Classification of Shorelines

It is highly desirable to be able to predict the potential impact of a spill on a shoreline so that the most sensitive areas can receive the greatest level of protection. Making this type of a prediction is very difficult, however, because of the diversity of shoreline types and the environmental conditions that occur along these shorelines. Because of these problems, Gunlach and Hayes developed a system to classify shoreline types according to potential for oil spill impact. This system has been used to predict impact in areas where spills have not yet been observed.

Gunlach and Hayes developed the system for evaluating coastlines through a detailed field study of two major oil spills and many minor spills (5). In these studies they found that the long term distribution, potential for damage, and long term persistence of oil spills depends on 1) wind stress and water currents, 2) beach activity and grain size, 3) tidal stage, 4) wave energy 5) oil quantity and composition, and 6) the effects of ice when it is present. Gunlach and Hayes used these elements to develop a classification of coastal environments in terms of potential oil spill damage. The way in which this was done is briefly described below.

o Wind Stress and Water Currents. Oil movement on water is controlled by winds and surface currents. Most observers agree that winds transport oil at about 3% of the wind speed. This factor may vary somewhat between spills and some suggest that heavier oils are transported somewhat faster, although this has not been confirmed with accurate measurements. Since spilled oil moves at near 100% of the speed of currents, surface currents have a greater potential for moving spills than winds. A wind of 100 knots would only move a spill at 3 knots whereas the current in some areas may reach a velocity of 4 to 8 knots. In practice, the transport of spilled oil is hard to predict because it is affected by changes in 1) wind direction, velocity, and duration, 2) surface water currents, and 3) time of major oil release.

o Beach Activity and Grain Size. Beach activity refers to the erosion and deposition of sediments that occurs on the shoreline. Most beaches undergo a repetitive construction-destruction cycle caused by waves and tides. Flat, long-period waves move material onto the beach while steep, high frequency waves take it away. In addition, beaches respond to tidal cycles by sediment accretion or beach construction as the tide progresses from neap to spring conditions. Oil can be buried rapidly as a beach is being constructed, which makes cleanup more difficult. In addition, oil may also be buried by alongshore depositional-erosional patterns. On the other hand, oiled beaches subject to extensive erosion would soon be cleaned by natural processes.

The characteristics of sediments on beaches also affect potential

for spill impact. (Section 3.2 contains additional information on sedimentation.) Grain size affects the depth that oil may be buried on the beach since larger grains are more easily transported by waves than fine grain sediments. Oiled sediment results from oil sinking by gravity into the beach and by mixing with oil and sediments in wave action. The result is distinct layers of oil visible in the beach. Field studies show that both oil burial and oiled sediment thickness increase as the grain size of sediments increase. On fine-sand beaches, oil penetration is generally limited to the upper few centimeters.

o Tidal Stage. In general, the stage of the tidal cycle is important to the surface distribution and ultimate persistence of oil on a shoreline. Extensive oil accumulations can be expected to wash ashore during spring tides. If waves are also present, the oil may be pushed up to the high tide area where debris accumulates along the highest portion of the beach. As the tidal cycle returns to neap, the deposited oil will remain above significant wave or swash activity. Oil coming onshore as the tide is going toward spring conditions is particularly hazardous since it is likely to be buried at the berm crest and remain above the normal erosive area of the waves. In the Alaskan Arctic the tidal range is only 15 to 30 cm, therefore tide effects are not as important as they may be elsewhere.

o Wave Energy. Field studies show that wave action on the shoreline is very important during and after spill impact. In the spills studied, oil was quickly eliminated from zones exposed to direct wave attack. For example, the oil from the METULA remained on the highest and lowest portions of the beach, which are areas of limited wave activity. In another spill, cliffed rocky headlands subject to high wave energy showed almost no environmental damage as a result of spilled oil. The reflection of the waves off the steep rocky cliffs held the oil offshore. On the other hand, areas sheltered from wave action, including rocky coves, tidal flats and marshes, had heavy accumulations of oil and showed the greatest environmental damage.

o Oil Quality and Composition. The type, condition, and amount of the spilled oil also affects the potential for damage to the shoreline. For example, light oils evaporate rapidly so that less oil is available to contaminate shorelines. Further, lighter oils are more likely to be dispersed naturally in the water column and penetrate deeper into the beach. On the other hand, heavier oils leave "paving" type residues that remain stranded on the beach.

The quantity of oil available not only affects how much of the beach will be covered, it also affects where it will be covered. If only a small amount of oil is available, it is usually deposited along the high-tide swashline. When more oil is available, it is likely to cover the entire beach face.

o Interaction With Ice. Ice is important to the behavior of a surface spill. This has been covered in great detail in Section 3. An important consideration that was only mentioned briefly before is that ice may transport oil great distances and contaminate other areas. This would be particularly important in the impact on distant shorelines.

4.5 Classification According to Retention Index

The preceeding section describes the concept of shoreline classification according to oil spill vulnerability developed by Gunlach and Hayes. Their classification assigns a vulnerability index to each shoreline segment

based on the energy level of the environment, the time the oil remains on the shore, and the potential for biological damage in the environment. Their shoreline categories range from straight, rocky headlands (Vulnerability Index=1, the lowest) to protected estuarine salt marshes (Vulnerability Index=10, the highest) (5). This system works very well for shorelines in the lower latitudes, but it does not apply as well to the Arctic because of differences in shoreline types and differences in physical processes. The next problem was to develop a similar system for the Arctic. Professor Dag Nummedal of Louisiana State University developed the arctic system as a research project for the Outer Continental Shelf Environmental Assessment Program (OCSEAP) (4).

Nummedal used the spill Vulnerability Index system as a starting point and developed a special index for the coastal zone of the Beaufort Sea (4). Nummedal's index differs from the original vulnerability index in two ways.

First, the index is called a <u>Retention Index</u> because it represents a measure of the persistence of stranded oil, but not necessarily the environmental impact of the oil. Environmental impact involves both species sensitivity and habitat sensitivity. The Retention Index is a measure of spill persistence in sensitive habitats, and therefore provides an index that correlates with, but is not identical to, a biological measure of habitat sensitivity.

Second, Nummedals's Retention Index system recognizes that the coastal environments of the Arctic differ significantly from those of temperate latitudes; therefore, the new system required a complete description of the Beaufort Sea coast shoreline types that were not included in the original Vulnerability Index scheme. Nummedal uses eight shoreline types that relate the mechanical energy that tends to remove stranded oil to the physical characeristics of the shoreline that tend to retain the oil.

Before continuing with the description of Nummedal's work, it is appropriate to pause briefly to give the reader an idea of how the new classification system was developed for the Arctic. The entire Alaskan Beaufort Sea coast was evaluated according to oil spill retention potential on a series of 30 charts, which are also presented in this Field Guide. These charts were developed in the field on the North Slope. During the summers of 1977 and 1978 Nummedal led a scientific team that sampled, photographed, and described the entire Alaskan coast from Pt. Barrow in the west to Demarcation Point in the east. Beach samples spaced 5 nm (9 km) apart were taken over the entire coast. The sampling stations are noted on the charts with a designation "BE" plus the number of the sample. The team also obtained nearly continuous oblique aerial photography that was annotated with detailed descriptions read on tape while flying over the area. Other sources of information include vertical aerial photography from commercial sources, coastal charts from the National Ocean Survey, and U.S. Geological Survey topographic maps.

4.5.1 <u>Spill Retention Index</u>

Shoreline types have been classified in eight categories in terms of the estimated persistence of the spill on the shoreline and the potential for environmental impact. The Retention Indices are numbered 1 through 8 with number 1 corresponding to the least persistent spill and potential for impact, and number 8 corresponding to the most persistent spill and the greatest potential for impact. Table 4.1 lists each Index and summarizes persistence

characteristics and potential for spill impact.

Each Spill Retention Index is defined in detail in the paragraphs that follow. Each paragraph number corresponds to a Retention Index numbered 1 through 8. Illustrations 4.1 through 4.12 show examples of the shoreline types. These photographs were made by Nummedal's team as a part of the field survey.

1. Steep Cliffs

Steep cliffs are restricted to shoreline exposures of ice-bonded permafrost. These cliffs are thermally unstable and subject to high rates of retreat. Cliff collapse generally occurs through a combination of undercutting by wave notching, mechanical failure of the ice-bonded block, and ice melting. Along exposed shorelines the released material is immediately removed by wave action, which

Table 4.1 Oil Spill Retention Potential. This table shows the Retention Index and summarizes persistence characteristics and potential for spill impact for typical environments on the Alaskan Beaufort Sea Coast.

Retention Index	Environment	Persistence	Impact
1	Steep cliffs	Little to none	Low
2	Steep beaches and bluffs of unconsolidated sediments	1 to a few years	Slight
3	Exposed non-vegetated barriers	1 year	Wide impact area but low species density
4	Vegetated low barriers	Many years	Impact on vegetation and wildlife
5	Lagoon-facing mainland shores	Many years	Oil released periodically to other sensitive areas
6	Peat shores	Many years	Serious affect on nutrient chain
7	Sheltered tidal flats	Many years	Large area contamination of organic debris
8	Marshes	> 100 years	Serious impact on Arctic ecosystem

helps to maintain the vertical cliff. Retreat rates can be as high as 20 m per year. Illustration 4.1 shows an example of steep cliffs characterized by Retention Index 1.

o Impact - Along the virtually tideless Beaufort Coast the oil would, at worst, coat only a narrow band on a vertical cliff. During storms the combination of a surge and wave splash could coat the cliff a few meters above mean sea level. The strong wave reflections that occur in front of these steep cliffs may keep the oil offshore.

o Persistence - Oil trapped on the cliff face will rapidly flow down and re-enter the nearshore water as a result of rain wash, cliff melting, and retreat. No oil would be retained over long time periods. Oil stranded in crevices or sprayed onto the tundra mat on top of the cliff could persist for a long time.

o Protection - Protection of this shoreline type would not be a high priority. The only effective means of protection would be offshore oil containment and removal.

o Cleanup - Cliffs would generally be self-cleaning. Oil accumulated in crevices and pools on the tundra surface would have to be manually collected.

2. Steep Beaches and Bluffs of Unconsolidated Sediments

Steep, narrow beaches generally occur in front of unconsolidated cliffs of tundra. The dominant particle size of the sediments in the tundra cliff controls the nature of the beach. If silt and clay dominate, there may be no beach because the fine sediments are continually removed in suspension. This formation is common along the Beaufort coast west of the Kuparuk River delta. Sand and gravel beaches occur in front of sandy and gravelly bluffs. The bluffs to the east of Prudhoe Bay are composed of coarse sediment and boulders backed by steep cliffs. Numerous boulder areas also occur farther west. Illustrations 4.2 and 4.3 show examples of these formations.

o Impact - The grain size of the beach determines oil penetration. Light oils can penetrate sand to a depth of a few centimeters. Medium and heavy oils can penetrate gravel (but not sand) to a depth of as much as a meter. In spite of these differences, the steep shorelines are all grouped together and characterized by a low retention index because a) the width of the coastal zone impacted by a potential oil spill is narrow, b) steep cliffs occur in high-energy zones where natural removal is effective, and c) wave reflection during storms may be effective in keeping some oil away from the beach.

o Persistence - The retreat rate of unconsolidated bluffs is not as high as that of vertical ice-bonded cliffs. Nevertheless, a retreat rate in excess of a meter per year would be expected. Therefore, even in the case of deep oil penetration into gravel, the oil-stained sediment would probably only have a residence time of one or at most, a few years. Oil on the face of the bluff would easily be removed by wave spray, rain wash, or gravity slumping.

o Protection - Offshore containment is the only effective method of protection.

o Cleanup - Manual cleanup would be effective on sandy beaches. The bluff should be left to natural self-cleaning. Hydraulic flushing, which generally is recommended for rocky cliffs and headlands, would cause erosion of the unconsolidated tundra bluffs and further mix oil

and sediment on the beach face.

3. Exposed, Non-vegetated Barriers

Most barrier spits and islands along the Beaufort coast are not vegetated. The low relief islands are subject to occasional complete surface reworking by storm tide overwash and ice push. These barriers are gravelly, or sand mixed with gravel. These shorelines retreat at rates of 3 to 7 m per year. Illustrations 4.4 and 4.5 show non-vegetated barriers.

o Impact - Coarse sediments permit deep penetration of any grade of spilled oil. (If the oil is highly viscous by the time it reaches the shoreline, only particles of the oil may be able to penetrate the sediments.) The low relief would cause a wide impact area. Thus, spilled oil would tend to be retained on the barrier islands. Biological impact on a non-vegetated barrier would be minimal, because these barriers generally have a very low species density.

o Persistence - Only exposed barriers are subject to high-energy wave conditons. Shoreline retreat rates, efficiency of overwash, and intense ice-push will make it unlikely that significant amounts of spilled oil will be retained on a Beaufort barrier more than a year. Exceptions to this evaluation may be found in local backbarrier swales.

o Protection - Most Beaufort barriers form the outer boundary of large shallow-water lagoons. The critical consideration for a spill drifting toward a barrier island chain, therefore, is to prevent oil from entering the lagoon area. Protective efforts using containment booms should be focused on the tidal entrances. The barriers form natural booms and their oil-stained beaches would probably cleanse themselves in a year.

o Cleanup - Because of the short residence time predicted for oil on the barrier beach, large scale cleanup is not recommended. Manual cleanup may be effective on short sections of sandy barrier beach. For the gravelly barrier beaches, however, the damage caused by large scale sediment removal would generally far exceed the damage by the initial impact of the oil.

4. Vegetated Low Barriers

This group includes barriers with some back-barrier sections old enough to have developed a vegetative mat of masses and grass and perhaps a permafrost core. Also included are low, flat beaches that grade landward into tundra, as well as perched beaches on top of the tundra. Sheltered tidal flats that would have a Retention Index of 7 are included in this retention category if their margins are protected by large dunes that would limit the landward penetration of an oil spill. Illustration 4.6 shows a low vegetated barrier.

o Impact - The impact on a barrier in category 4 would be more severe than on barriers mentioned previously because vegetation is generally associated with a highly productive ecosystem. Bird nesting grounds are widespread on vegetated barriers. The other impact factors would correspond to those discussed in category three.

o Persistence - Oil persistence would be greatly increased over non-vegetated barriers for two reasons: a) the presence of vegetation would provide a greatly increased surface area to which the oil could adhere, b) the presence of vegetation demonstrates infrequent water flushing and ice-push. Once oil has entered a vegetated back-barrier or back-beach environment it could persist for many years until removed by processes of biological rather than mechanical

degradation.

o Protection - Oil could enter vegetated back-barrier environments either through storm overwash from the ocean beach or through flooding by water from an oiled lagoon. Flooding from a lagoon would probably be the most common. The best protection would therefore be to block oil entrance through the tidal passes.

o Cleanup - Pools of standing oil could be recovered. Oil-stained vegetative matter should be left to biological degradation. The use of heavy equipment should be kept to an absolute minimum because mechanical disruption of the tundra surface may have far more serious long range environmental effects than the oil.

5. Lagoon-facing Mainland Shores

This category includes a wide range of shoreline types, but they are all exposed to only moderate wave action. Generally there is a sand, or mixed sand or gravel beach. The beach is a few meters wide in front of a thermally retreating tundra bluff. Retention Index 5 is only used on charts where the tundra bluff is high enough to prevent oil penetration farther inland. (In areas of low bluffs or no bluffs, a higher Retention Index applies.) Illustration 4.7 shows a sand and gravel beach backed by a tundra bluff.

Another example of Retention Index 5 includes the lagoonal mainland shore with a zone of collapsed tundra with sod-covered blocks forming a jumbled transition from the unbroken tundra surface to the lagoon.

A third example of this category is a lagoonal mainland shore with a flat platform, generally muddy or sandy, with a surface layer of large boulders.

o Impact - Oil deposited on the lagoon beaches would initially have no more impact than that on exposed beaches with a Retention Index of 2. Because of low wave energy, however, removal would be quite slow. Oil from lagoon beaches could be released again to the marine environment over a period of years after the initial impact. The low wave energy of the lagoon prevents the development of long, uniterrupted beaches. Instead, the mainland shore is marked with many river mouths, small tidal inlets, marsh entrances, coves, and low organic rich bluffs. Oil released from lagoon beaches any time after the initial impact would be free to enter any of these environments in the absence of continuous human monitoring and protection.

o Persistence - Oil introduced into this environment would be expected to last for years because of the low transport rates, the moderate shoreline retreat rates, and the irregularly embayed nature of the lagoonal mainland beach. Biological and mechanical processes would be expected to play about equivalent roles in degradation of the oil.

o Protection - Protective measures would have to be carried out in the lagoon entrances to be effective. The prevailing winds would quickly distribute the oil along wide sections of the mainland shore once it entered the lagoon. On the other hand, mechanical recovery devices could operate more effectively in the lagoons because of low wave action and a general absence of floating ice during the summer months.

o Cleanup - Cleanup measures on the narrow mainland beaches should be designed to protect the tundra margin. Damage to the tundra would accelerate the rate of shoreline retreat.

6. Peat Shores

Large amounts of peat detritus are mixed with inorganic sediments in the tundra bluffs. In addition, the surface tundra mat may be many feet thick. This abundance of organic material and low wave energy results in an unique arctic peat shore that occurs in three forms:

1) Peat fragments eroded from headlands accumulate in adjacent embayments where they form a wide peat beach-ridge plain. Illustration 4.8 shows a peat beach ridge plain. Generally, the deposit is reduced into a thick mass of floating peat that resembles coffee grounds and becomes more dispersed seaward. The floating peat acts as a very efficient energy-absorbing wave attenuator. Locally these peat deposits form spits. Illustration 4.9 shows peat floating in an embayment.

2) Subsiding mainland marsh appears in places to have come so close to sea level that frequent storm inundation has destroyed the tundra vegetation. These areas are characterized by wide plains with peat mixed with mineral matter. Illustration 4.10 shows a shoreline with a typical deposit that resembles coffee grounds.

3) A variation of 2) in which some sand and gravel have been added to the system in the form of a small beach perched on the peat surface.

o Impact - Peat is an important nutrient along the shoreline. Oil staining the peat could have a serious effect on the entire nutrient chain. This problem is compounded by the fact that peat is such an effective oil collector that it is often used as a sorbent to collect spilled oil.

o Persistence - The floating peat shores appear to have very low erosion rates. In fact, in many places they are actively accreting. In addition, because waves are completely attenuated before reaching shore, there would be no mechanical processes of oil degradation in this environment except during major storms when the peat shore may be completely broken up. The peat shores would probably retain oil for many years.

o Protection - Peat accumulations are not long but they occur frequently along the shore. Efforts should be made to keep floating oil slicks away from these deposits.

o Cleanup - Contaminated peat could be removed physically. Bulk removal, in spite of the physical destruction of the immediate shoreline, might be preferable to the circulation of all the hydrocarbons through biological action in the lagoon.

7. Sheltered Tidal Flats

The outer margin of most major river deltas along the arctic slope consists of featureless fine sand tidal flats. These tidal flats also have mud accumulations, but coarse sediments in streams generally settle out before they reach the coastline. The discharge of arctic rivers is highly seasonal, with the peak discharge occurring at the time of the early summer snow melt. In fact, a large percentage of the total annual discharge occurs within a 10 day period after break-up. Peak river discharge generally occurs while the nearshore zone is still ice covered. Sediment deposits on the ice extend many kilometers offshore. Shortly after the river flooding the nearshore ice generally breaks up.

Most major river deltas occur at the head of shallow embayments or in lagoons. In both cases the nearshore wave energy is small. The deltas are completely dominated by the river flow and have no wave-built spits or bars along their seaward

margins. Storm surges, therefore, cause inundation of extensive areas of these sheltered delta tidal flats. Driftwood and finer organic debris reflecting storm-surge water lines commonly litter the flats. Illustration 4.11 shows a view of tidal flats. Polygon areas have a Retention Index of 8.

o <u>Impact</u> - Only the lightest grades of oil would penetrate the fine grains of the tidal flats. Abundant organic debris, however, would tend to absorb large amounts of oil. Because of the flat topography, even minor storm surges would cause spilled oil to stain large areas. Some tidal flats have sand dunes formed by wind along the channel banks. These banks have a lower Retention Index of 4 because there would be less oil coating of these surfaces.

o <u>Persistence</u> - The tidal flats have a high retention potential because the agents of mechanical removal are not present. Wave energy is virtually zero and therefore the the heavy sediment-laden asphalt left on the flats after a spill of heavy crude (or even highly weathered light crude) will not be broken down and removed by high water inundation during a storm surge. In addition, the seaward margins of the tidal flats are likely to be ice-covered during the spring flood preventing the river flow from removing the oil. The weathered oil entering and coating the river mouth tidal flats would most likely be protected from any form of mechanical degradation. Spill residues would be expected to last for years in these areas.

o <u>Protection</u> - Protection of tidal flats would be most effective through the use of booms in tidal entrances leading into the delta-front lagoon. The second line of defense would be to operate skimmers and other sea-surface oil collection equipment in the lagoon. The generally quiet water off the deltas could make such collection fairly effective.

o <u>Cleanup</u> - The fine-grained, firm, non-vegetated tidal flats could easily be cleaned manually. Oil penetration would be generally less than on sandy beaches. The oiled surface sediments could be removed by shovel and transported away by barge. Cleanup would generally be desirable in order to prevent oil from drifting from the tidal flats into the biologically productive marshes. Marshes commonly border many delta-front tidal flats.

8. <u>Marshes</u>

Because of the lack of a significant tide in the Alaskan Beaufort Sea, there are no true intertidal salt marshes. Brackish or saline marshes occur in vegetated low-lying coastal areas that are subject to frequent storm-tide salt water inundation. Although marshes are frequent, they individually occupy limited areas along the coast. There are two types of marshes, 1) those associated with river banks, estuarine and river deltas, and 2) those associated with low-lying tundra marked by ice polygons. (Ice polygons are formed by wedges of ice that penetrate into the ground.) The first marsh type has a high level of biological activity. The second type often occupies sites of partly drained thaw-lakes. At first the thaw-lake marshes may maintain the vegetation characteristics of the freshwater lake shores, but with increasing frequency of storm surge inundation they gradually change into above-tidal marshes. Illustration 4.12 shows a low marsh with ice polygons.

o <u>Impact</u> - Marshes play a significant role in the arctic ecosystem because of their high primary productivity and the fact that they are important habitats for many species

of birds and smaller mammals. <u>Oil introduced into an arctic marsh could seriously alter the biological balance.</u> Many marsh-dwelling species already live under rather stressed conditions because of rapid and sometimes dramatic changes in water level, salinity, and surface temperature. Destruction of large populations of organisms in a coastal marsh as a result of an oil spill could have significant effects on the whole chain of nutrient interactions in the arctic ecosystem.

o <u>Persistence</u> - Field studies of spills in other areas indicate that after some initial weight loss to evaporation, the weathered spill residues would be virtually permanent in salt marshes. Some removal of oil could be expected from river banks and estuarine marshes that are washed by river flooding. Mechanical degradation of oil by wave action and biological degradation of oil are also likely to be ineffective. Oil is expected to remain in salt marshes in the Strait of Magellan from the METULA spill for 100 years. Degradation of spilled oil in the Arctic is likely to be much slower.

o <u>Protection</u> - Most arctic marshes have a small area and generally exchange water with the arctic ocean through narrow river mouths or tidal entrances, often constricted by wave-built spits. As a result, marshes could be protected by booms deployed across these inlets. Keeping booms available to protect these areas should be a top priority.

o <u>Clean-Up</u> - Clean-up in a marsh would generally be counter productive.

4.6 <u>Spill Retention Charts</u>

Figures 4.1 through 4.30 show the oil spill retention potential for the Alaskan Beaufort Sea coast. Figure 4.0 provides an Alaskan Beaufort Sea Locator Chart. This figure shows where each of the spill retention charts are located along the Alaskan coast with the name of the most prominent landmark in the area.

The retention charts are arranged from east to west beginning at Demarcation Bay near the U.S./ Canadian border and extending west to Point Barrow. The range of longitude covered by each chart is shown in parens after the title to help in identifying specific areas. The scale is shown in kilometers. To help in transferring this information to nautical charts, recall that 2 km is approximately equal to 1 nautical mile. The source chart for each of these Retention Index charts is shown below the distance scale. .

Ground truth data were collected at sites BE 1 through BE 119. These sites are shown on the spill retention charts. The ground truth data sets consist of beach profiles, sediment samples, and photographs taken along the beach in two directions from the sample site. Each ground truth site was picked from the air as being representative of a given section of the shoreline. Each site was assigned an oil spill Retention Index based on the criteria described in Section 4.5. Sections adjacent to the ground truth site were classified by extending the site information using vertical and oblique air photos, descriptions read on tape while flying, and coastal charts and maps. In simple cases the shoreline was directly classified while flying.

The length of shoreline in each retention category was measured and calculated as a percentage of total shoreline within each chart square. The results are displayed as frequency histograms on each chart. These graphs are useful in quickly assessing the potential for spill impact in each chart area.

It is also instructive to sum up these histograms to determine the percentage of the entire Alaskan Beaufort Sea coast that falls in each Retention Index. Table 4.6.1 shows this result.

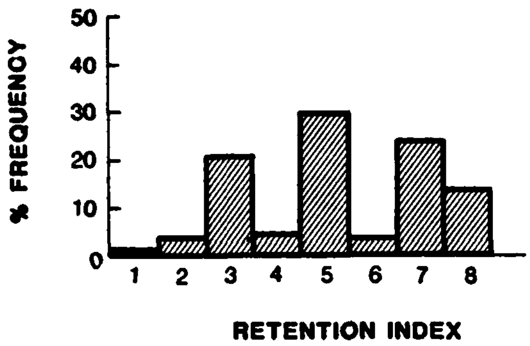

Table 4.6.1 Average Retention Index Frequency for the Entire Coastline

In terms of the spill Retention Index, the Alaskan Beaufort Sea has dominant coastal types. Table 4.6.1 shows that shoreline with Retention Indices of 3,5,7, and 8 includes 86% of the entire coastline. Some of these dominant coastline types are relatively safe in terms of oil spill impact and some are not. For example, about 20% of the coast falls in Retention Index 3, exposed non-vegetated barriers. These are the well-known barrier islands of the Alaskan coast. These islands generally would protect more sensitive areas, and because of the mechanical energy supplied from the Arctic Ocean, spilled oil is not likely to be retained for more than a year.

Table 4.6.1 also shows that 70% of the coastline has a Retention Index of 5 or more, which indicates a much higher potential for environmental damage. Retention Index 5 corresponds to a lagoon-facing mainland shores. (See Table 4.1 for a summary of shoreline types.) As noted in Section 4.5.1, spilled oil is likely to persist for many years because of low wave energy, and oil from these beaches could be released to the marine environment over a period of years after the spill. Although Retention Index 5 is just above mid-range for persistence and impact, the potential for environmental damage must be considered to be quite high.

Shorelines with Retention Indices of 6 through 8 are clearly areas where environmental impact from spilled oil would be great. Retention Index 6 identifies peat shores. Although these do not cover a large percentage of the coastline, peat is a great absorber of oil and the potential for environmental damage is high. Shorelines with Retention Indices of 7 and 8 include about 37% of the coastline. These are the sheltered tidal flats and marshes. These are highly sensitive areas with virtually no natural forces available to clean them out. Oil deposited in these areas would remain in place for years. There is no good estimate for the residence time, but it would be longer than for warmer climates, and the best estimate for these areas now is about 100 years. As a practical matter, oil that accumulates in areas 7 and 8 is likely to remain as a permanent feature.

ILLUSTRATION 4.1: RETENTION INDEX 1 Ice-bonded permafrost cliff west of Cape Halkett and of station BE 80.

ILLUSTRATION 4.2: RETENTION INDEX 2 Bluff and beach at Pt. Barrow.

ILLUSTRATION 4.3: RETENTION INDEX 2 Truncated sand dune and narrow beach at Harrison Bay.

ILLUSTRATION 4.4: RETENTION INDEX 3 Ice-push at Karluk Island in the McClure Islands group, station BE 25.

ILLUSTRATION 4.5: RETENTION INDEX 3 Cusps on a barrier beach in Camden Bay east of Brownlow Pt., station BE 17.

ILLUSTRATION 4.6: RETENTION INDEX 4 Beach at Atigaru Point in Harrison Bay, station BE 74.

ILLUSTRATION 4.7: RETENTION INDEX 5 Eastern shore of Harrison Bay, station BE 67.

ILLUSTRATION 4.8: RETENTION INDEX 6 Peat-rich outcrop at Tolaktuvuk Point in Harrison Bay, station BE 70.

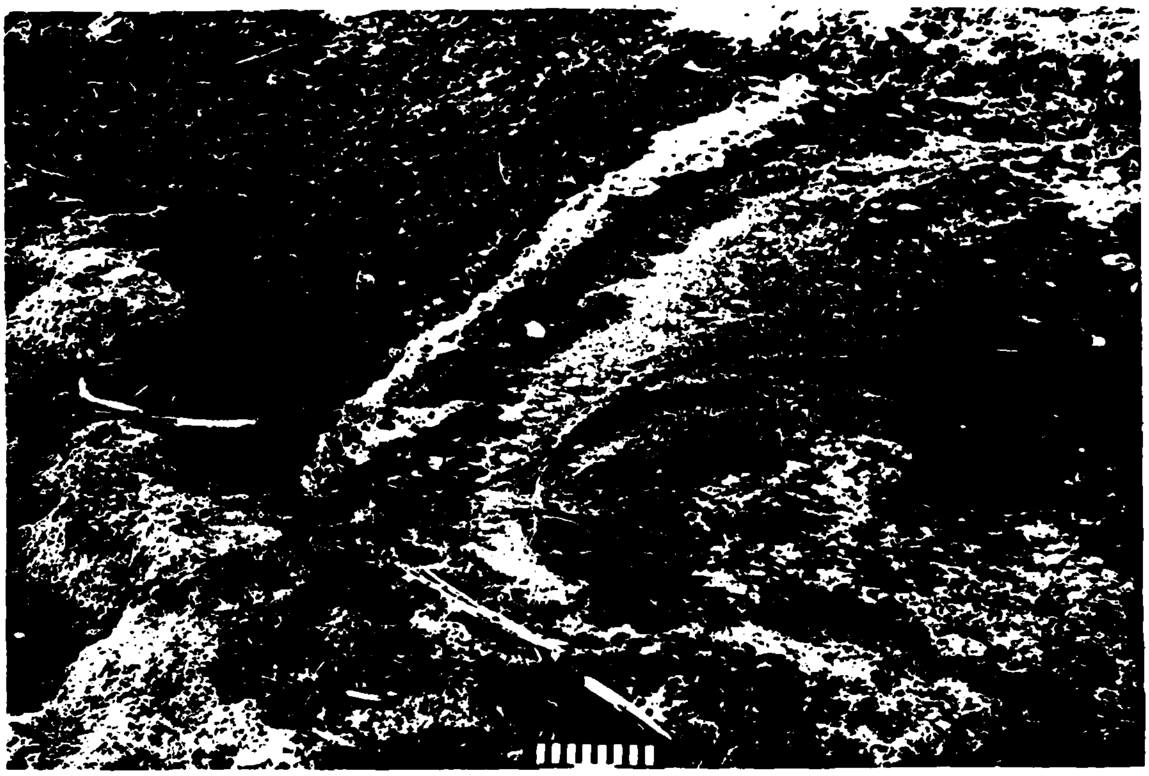

ILLUSTRATION 4.9: RETENTION INDEX 6 Floating peat trapped in a small embayment along the mainland shore of Simpson-Lagoon, station BE 65.

ILLUSTRATION 4.10: RETENTION INDEX 6 "Coffee-grounds" shoreline at Simpson Cove in Camden Bay, station BE 14.

ILLUSTRATION 4.11: RETENTION INDEX 7 The Ikpikupk River Delta at the head of Smith Bay. (Polygon areas have a Retention Index of 8.)

ILLUSTRATION 4.12: RETENTION INDEX 8 Low marsh in areas of polygonal ground at the margin of the Kuparuk River delta.

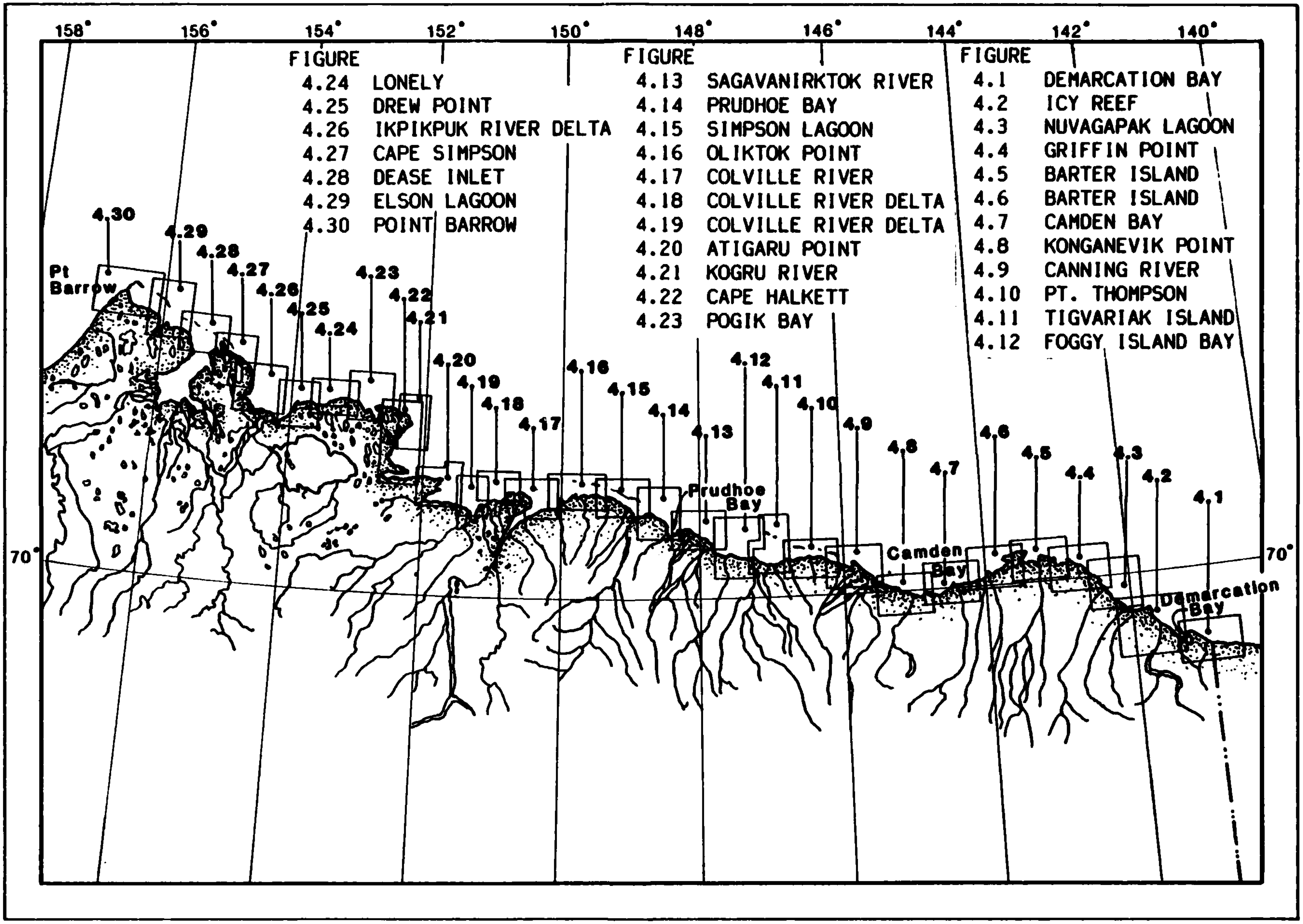

FIGURE 4.0 ALASKAN BEAUFORT SEA LOCATOR CHART

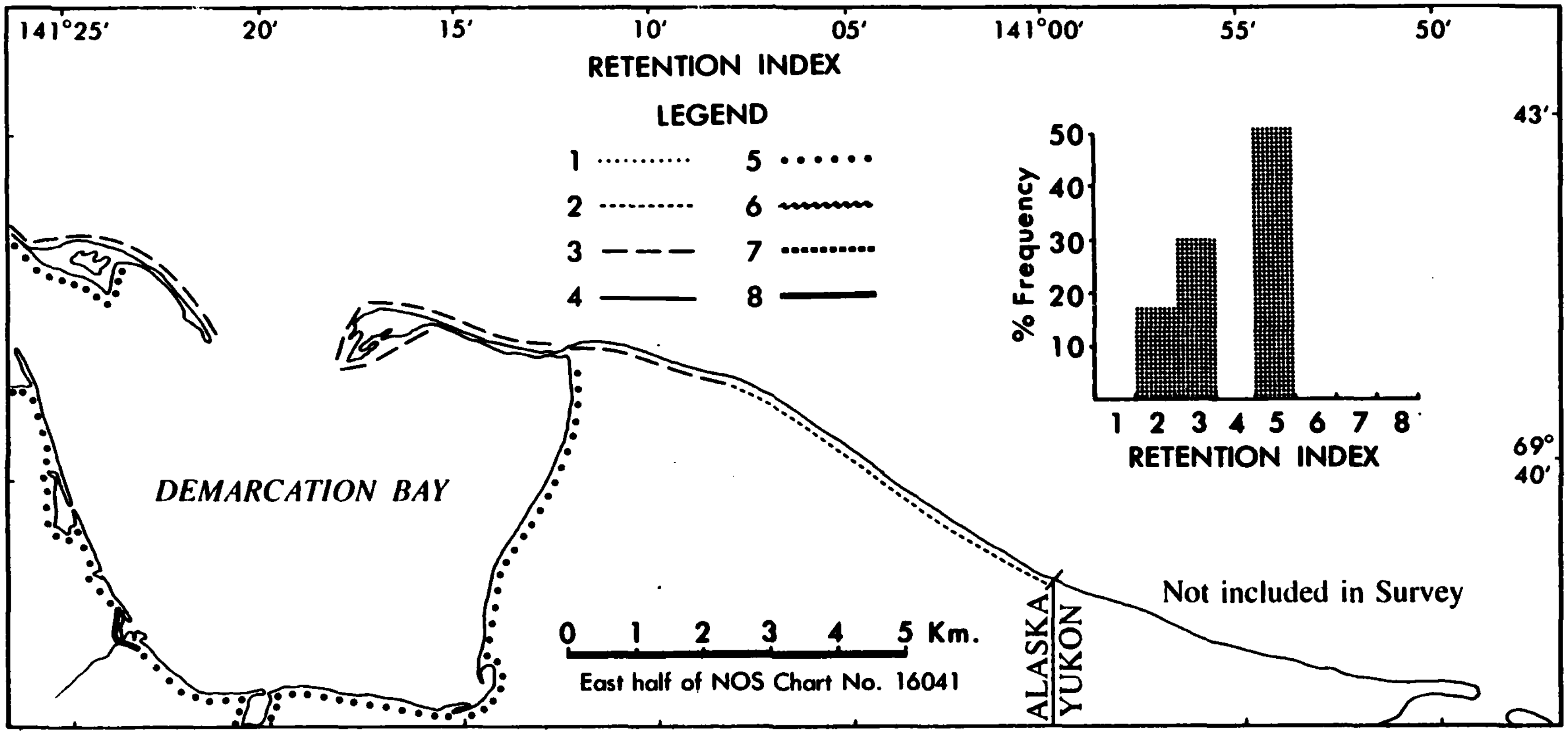

FIGURE 4.1 DEMARCATION BAY (141 to 141-25W)

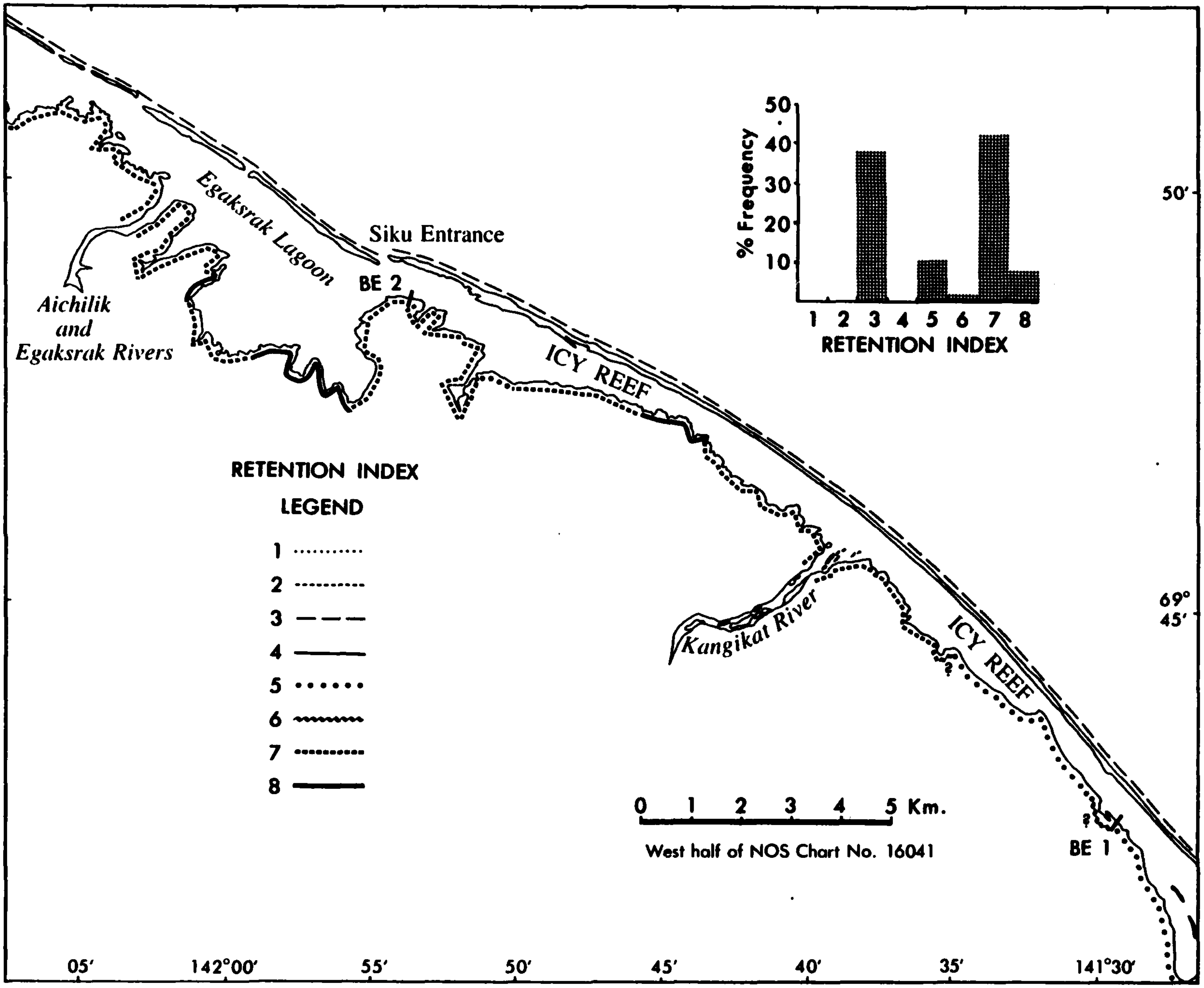

FIGURE 4.2 ICY REEF (141-25 TO 142-05W)

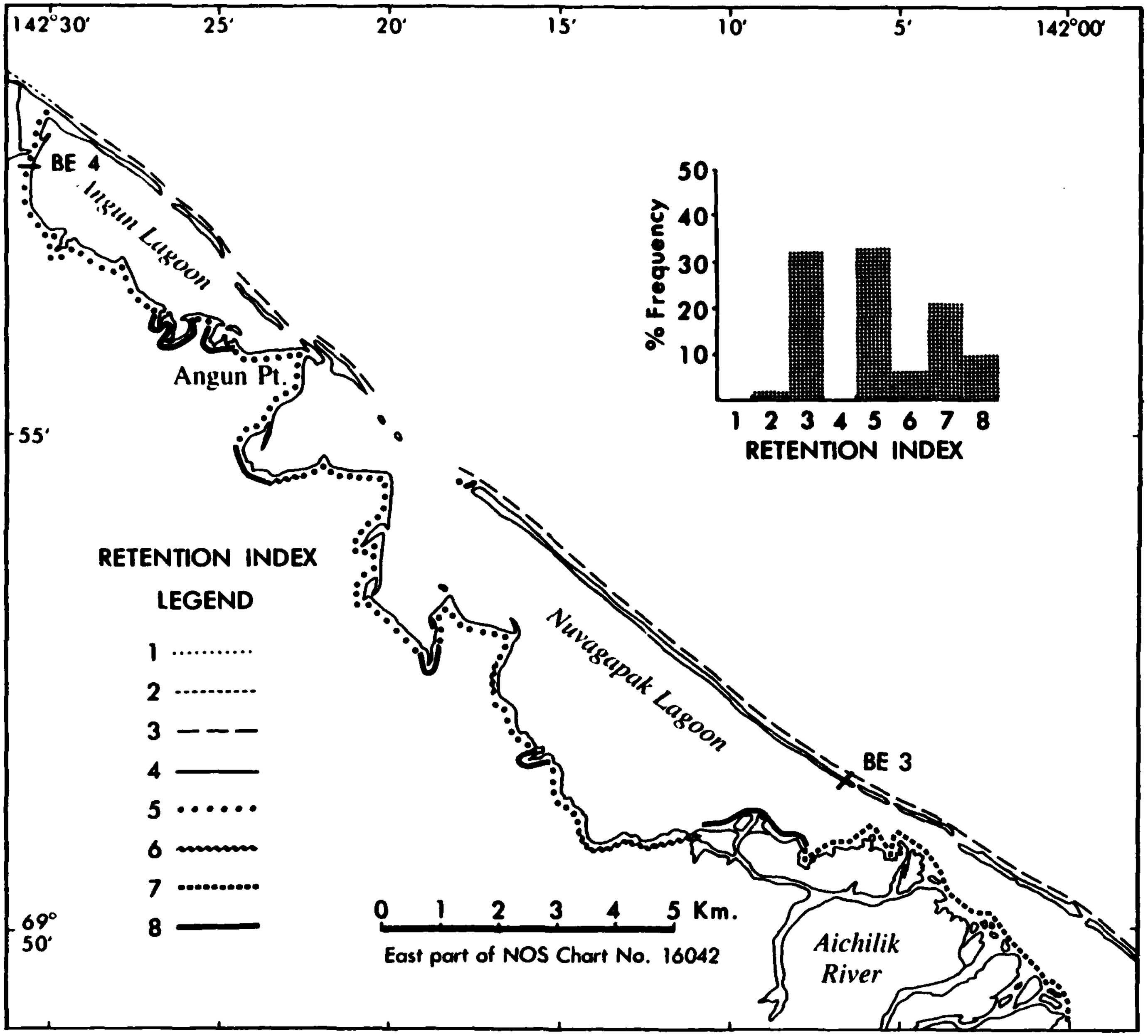

FIGURE 4.3 NUVAGAPAK LAGOON (142 TO 142-30W)

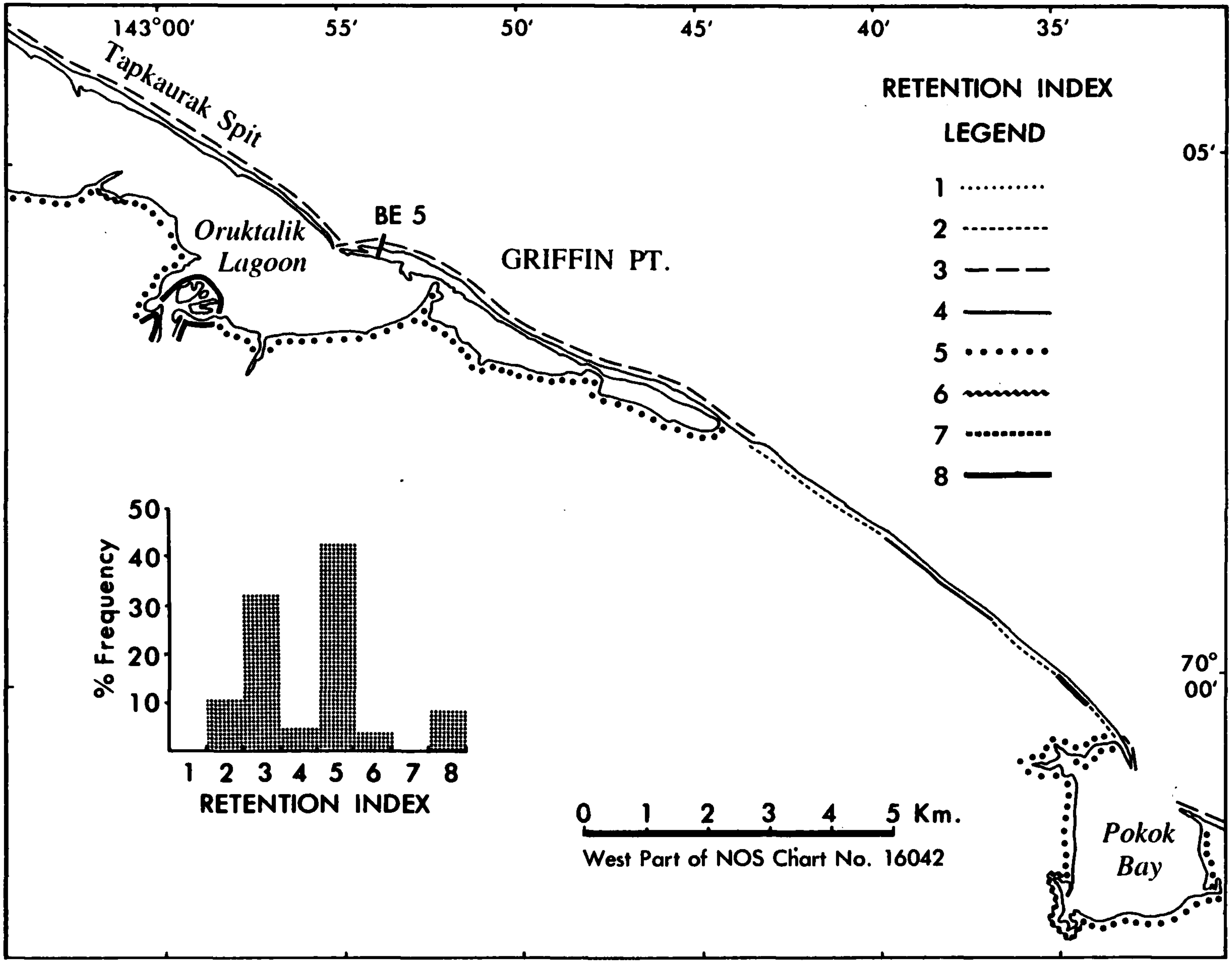

FIGURE 4.4 GRIFFIN POINT (142-30 TO 143W)

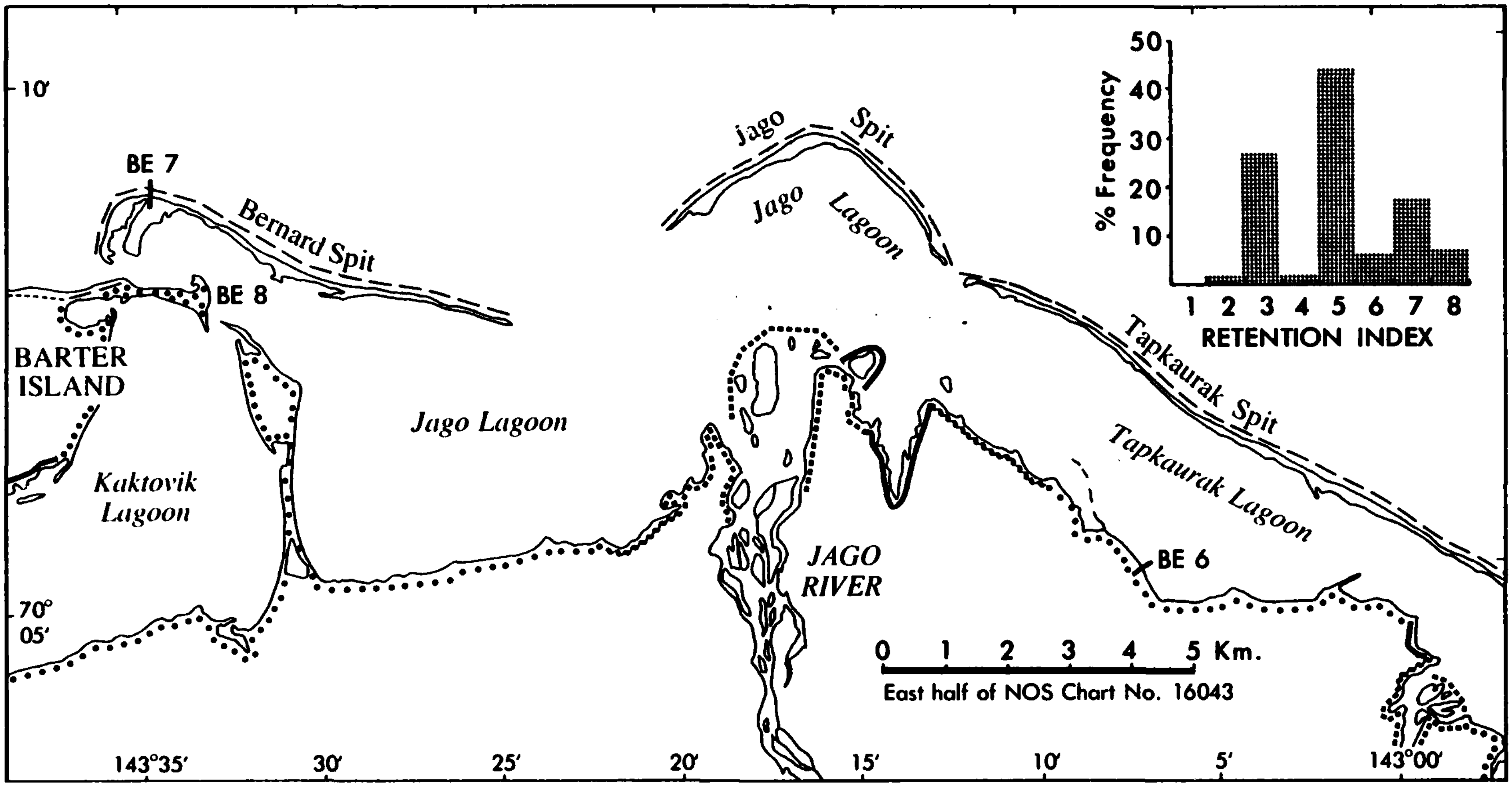

FIGURE 4.5 BARTER ISLAND/JAGO LAGOON (143 TO 143-35W)

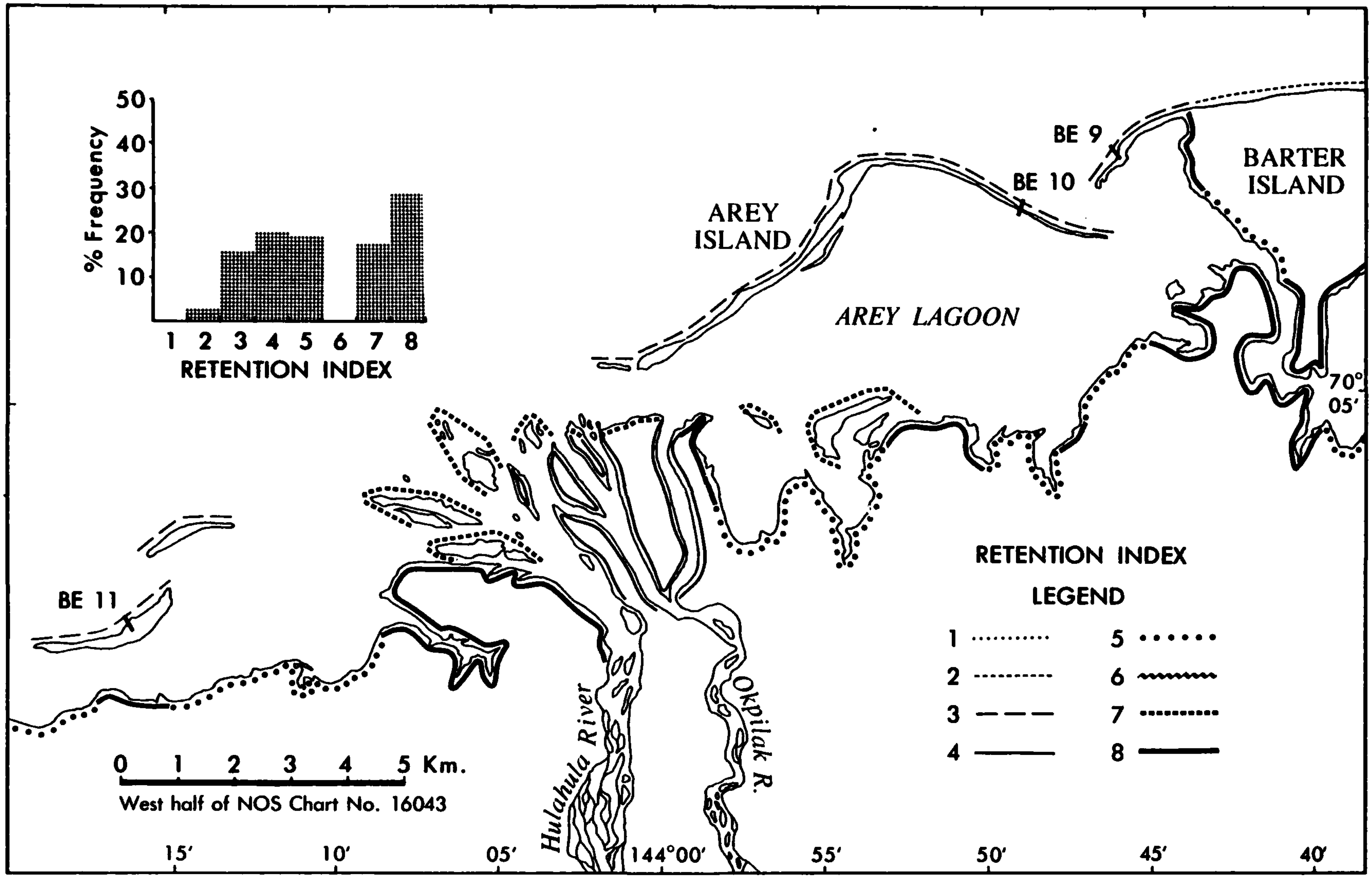

FIGURE 4.6 BARTER ISLAND/AREY LAGOON (143-40 TO 144-15W)

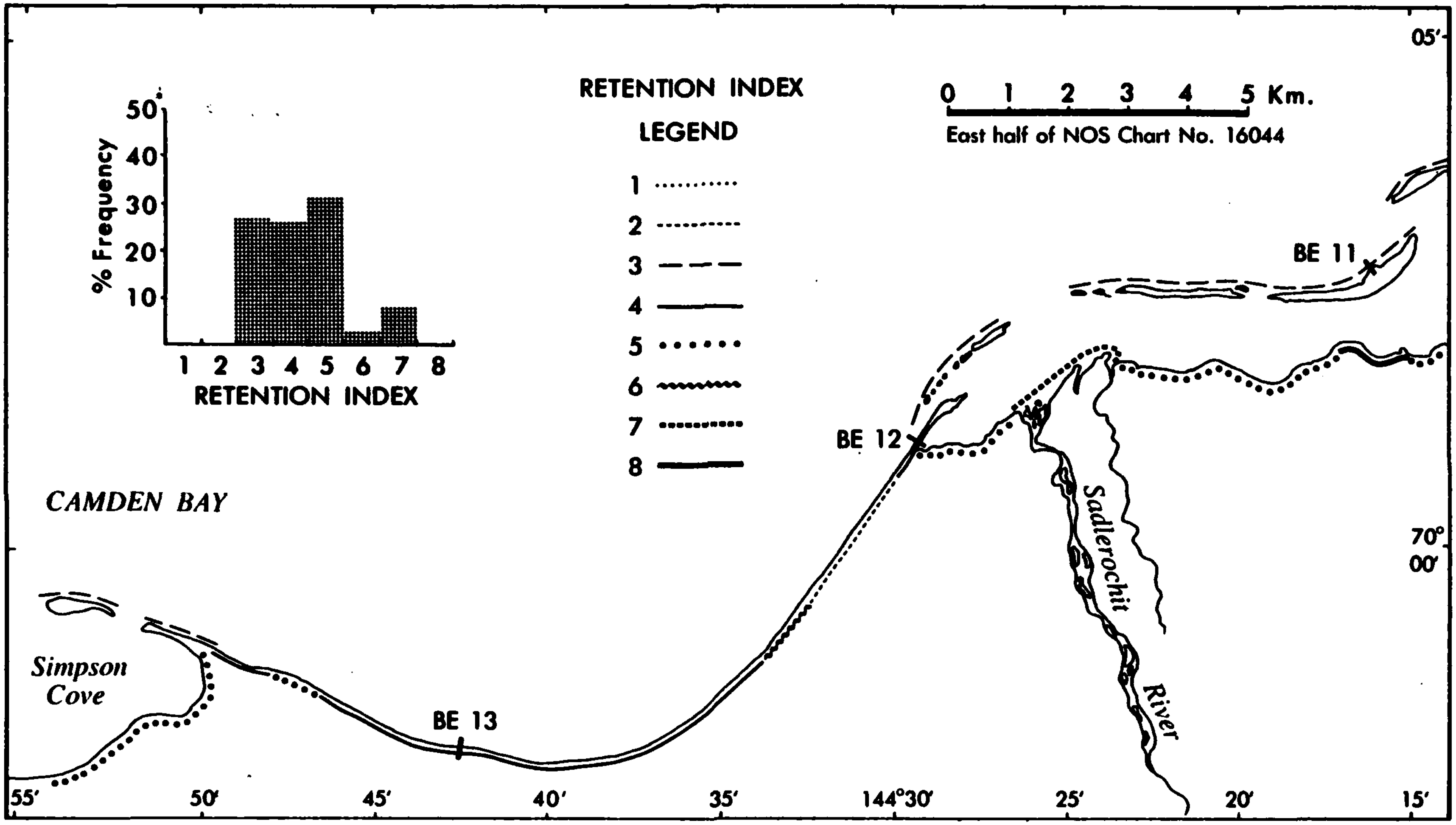

FIGURE 4.7 CAMDEN BAY (144-15 TO 144-55W)

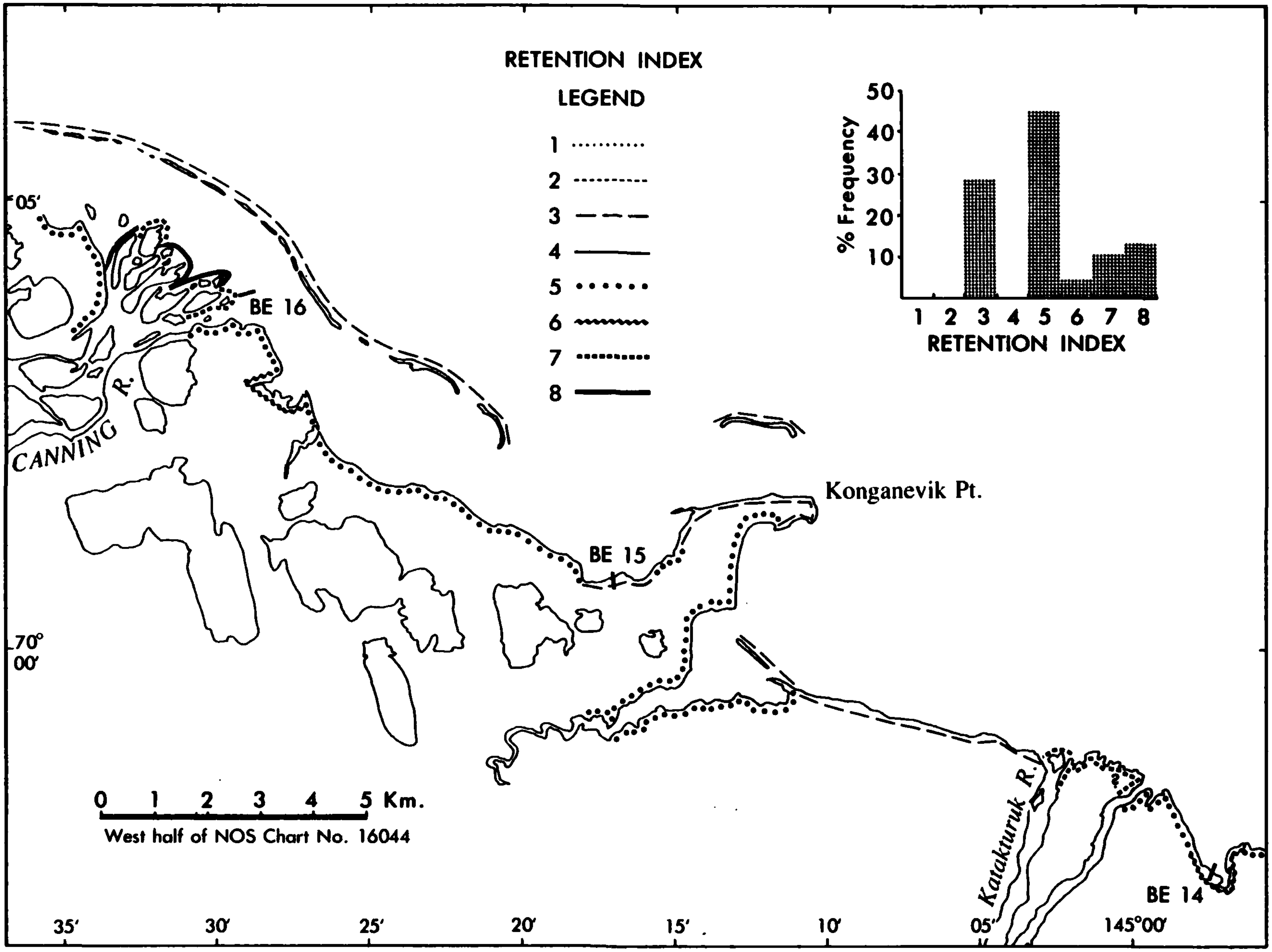

FIGURE 4.8 KONGANEVIK POINT (145 TO 145-35W)

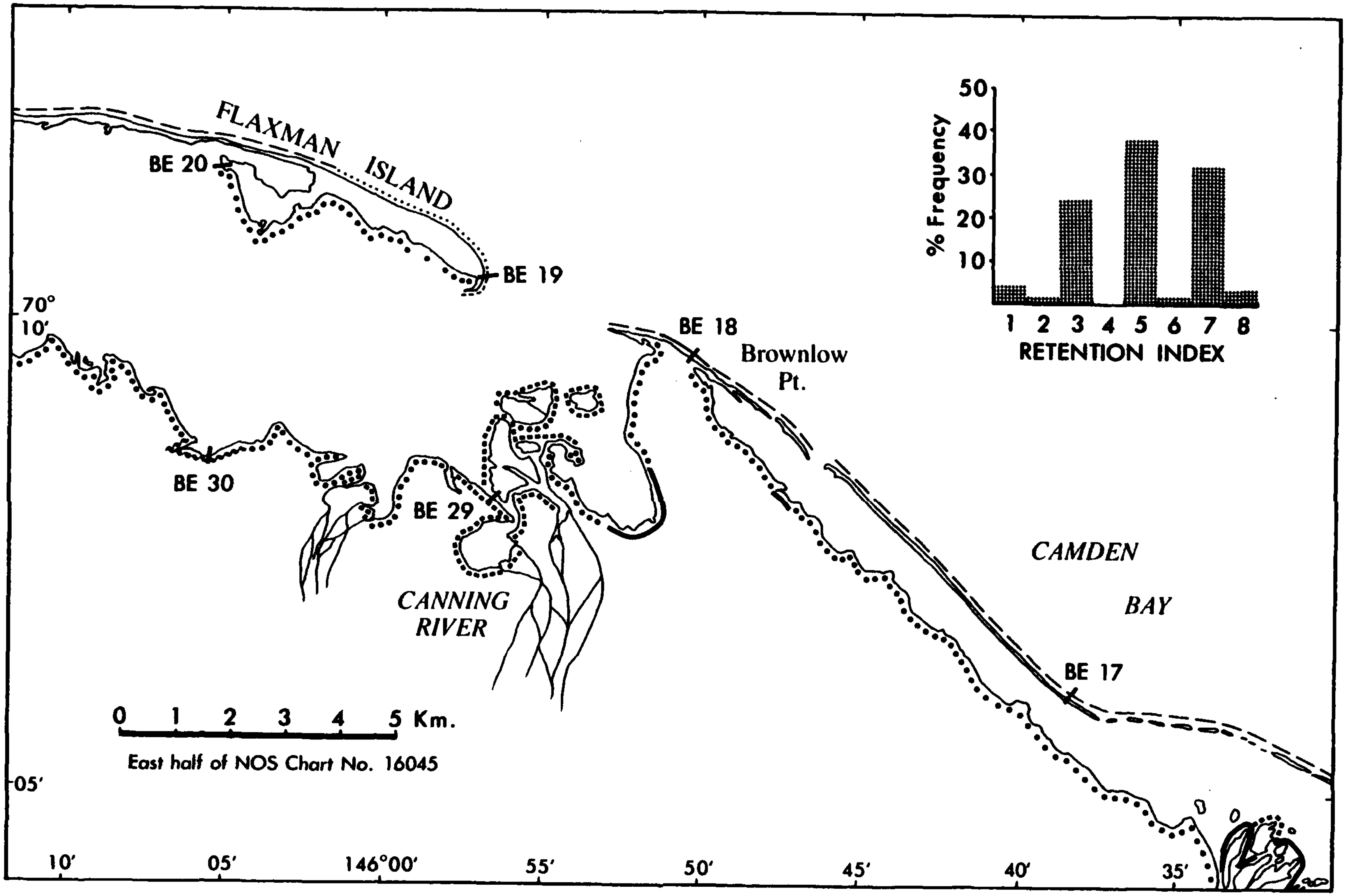

FIGURE 4.9 CANNING RIVER/FLAXMAN ISLAND (145-35 TO 146-10W)

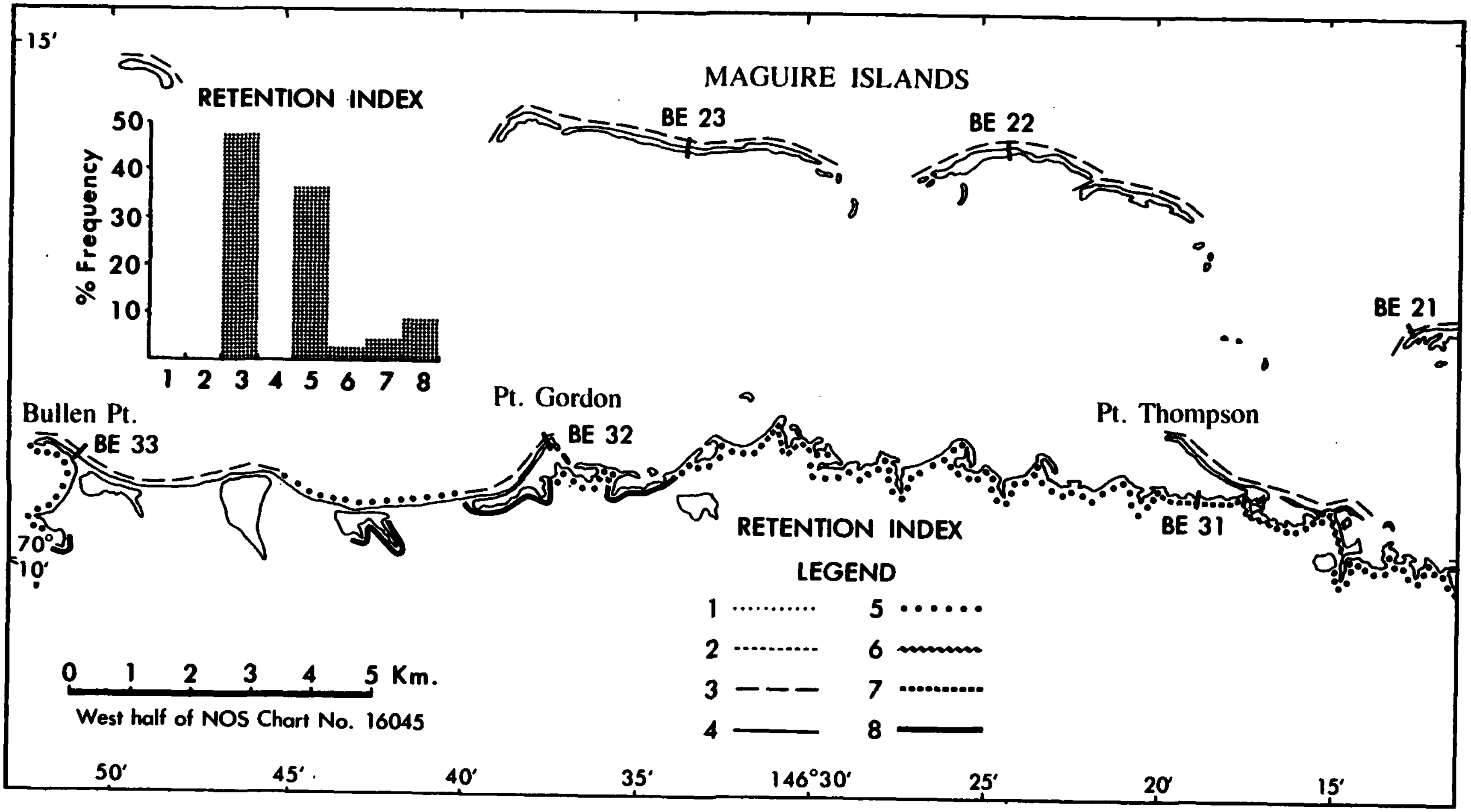

FIGURE 4.10 PT. THOMPSON/MAGUIRE ISLANDS (146-15 TO 146-50W)

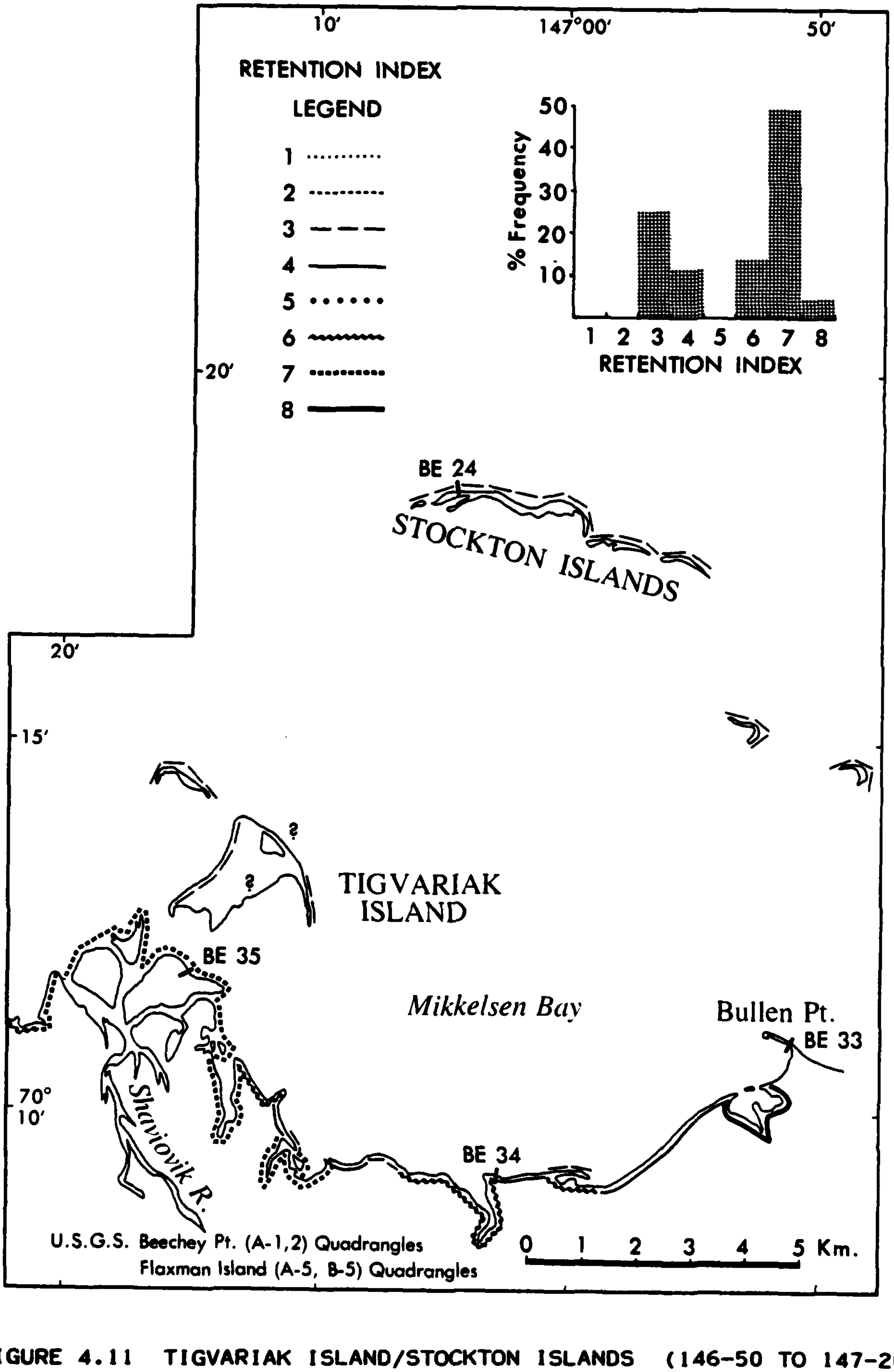

FIGURE 4.11 TIGVARIAK ISLAND/STOCKTON ISLANDS (146-50 TO 147-20W)

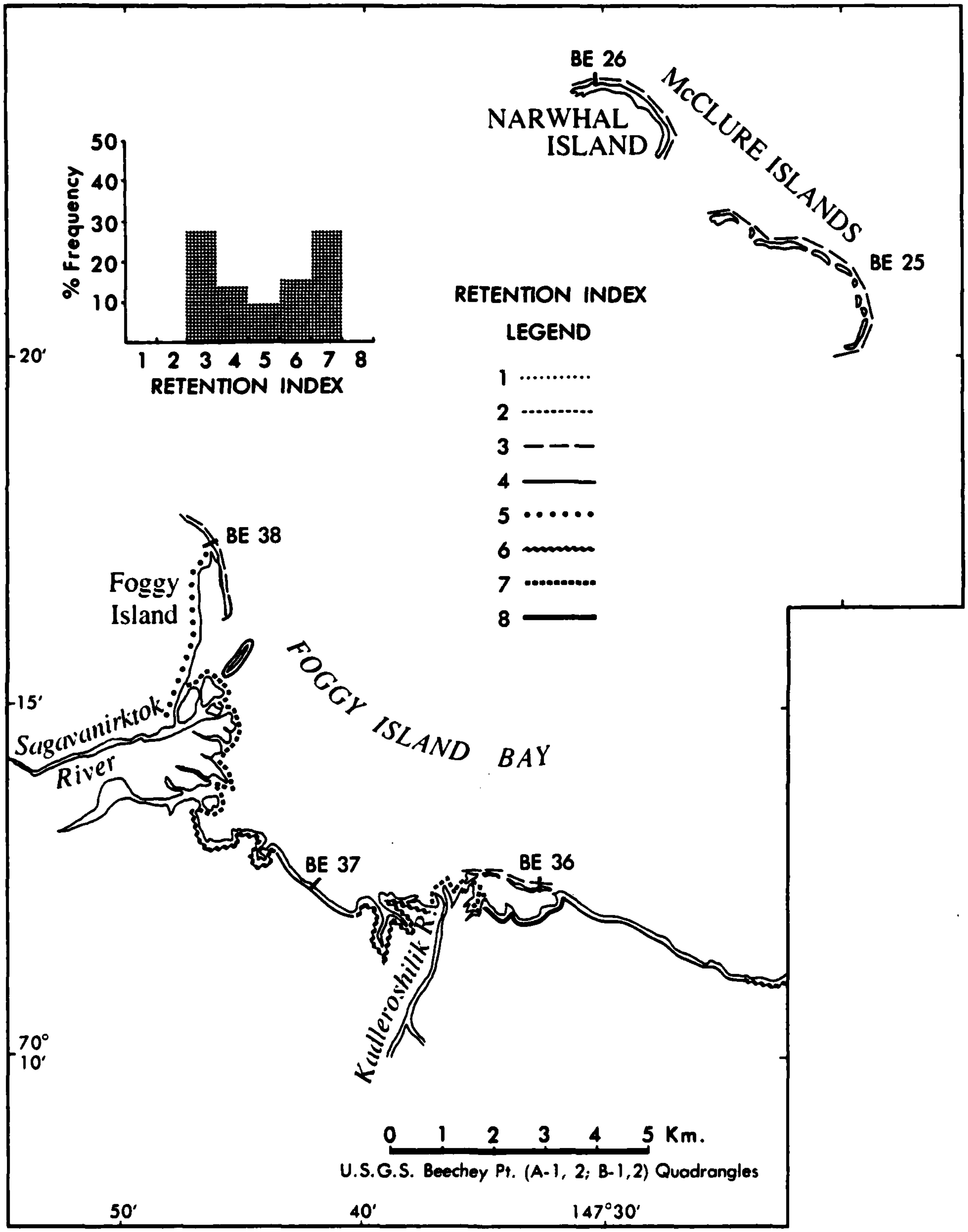

FIGURE 4.12 FOGGY ISLAND BAY/NARWHAL ISLAND (147-20 TO 147-50W)

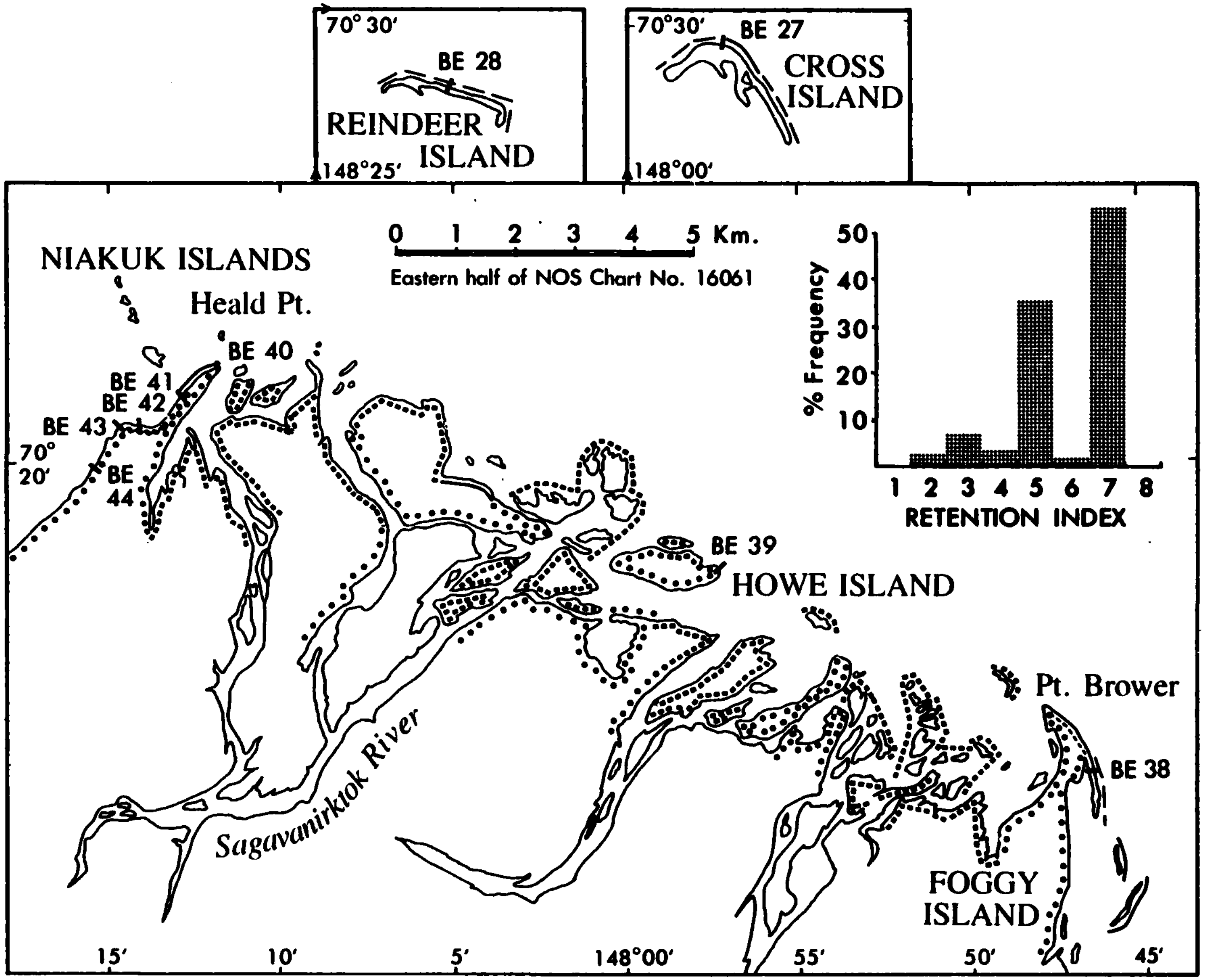

FIGURE 4.13 SAGAVANIRKTOK RIVER (147-45 TO 148-15W)

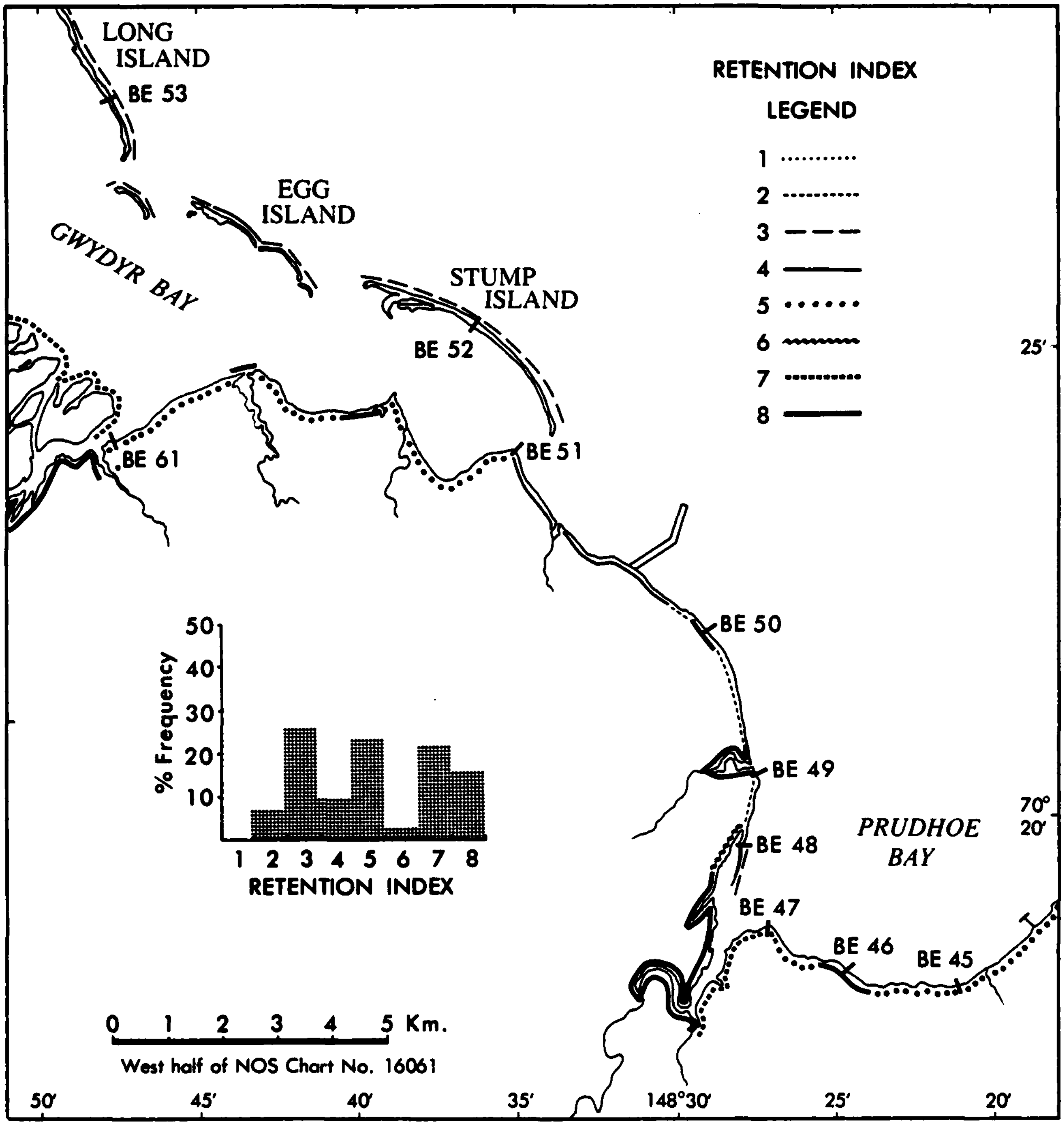

FIGURE 4.14 PRUDHOE BAY (148-20 TO 148-50W)

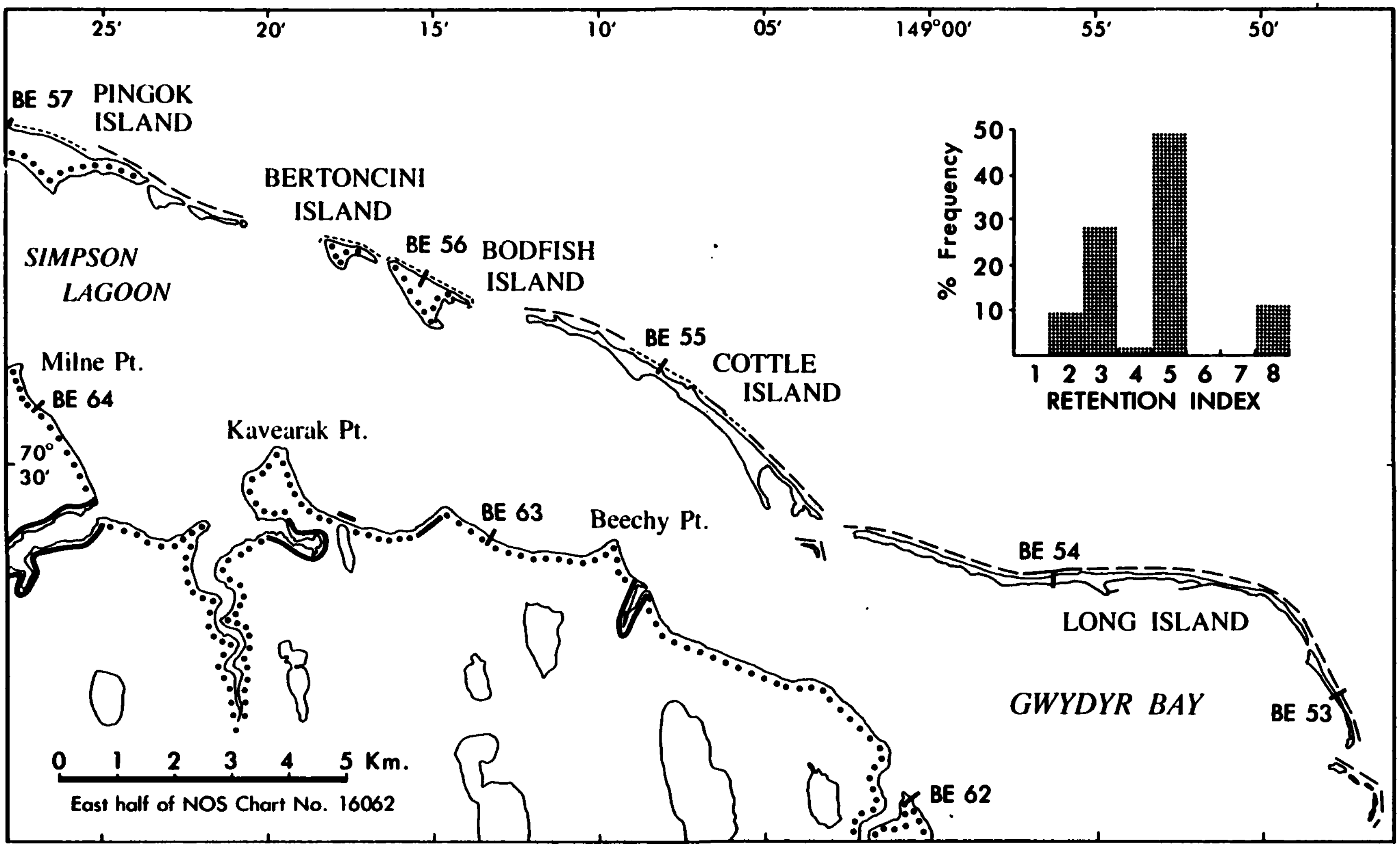

FIGURE 4.15 SIMPSON LAGOON (148-50 TO 149-25W)

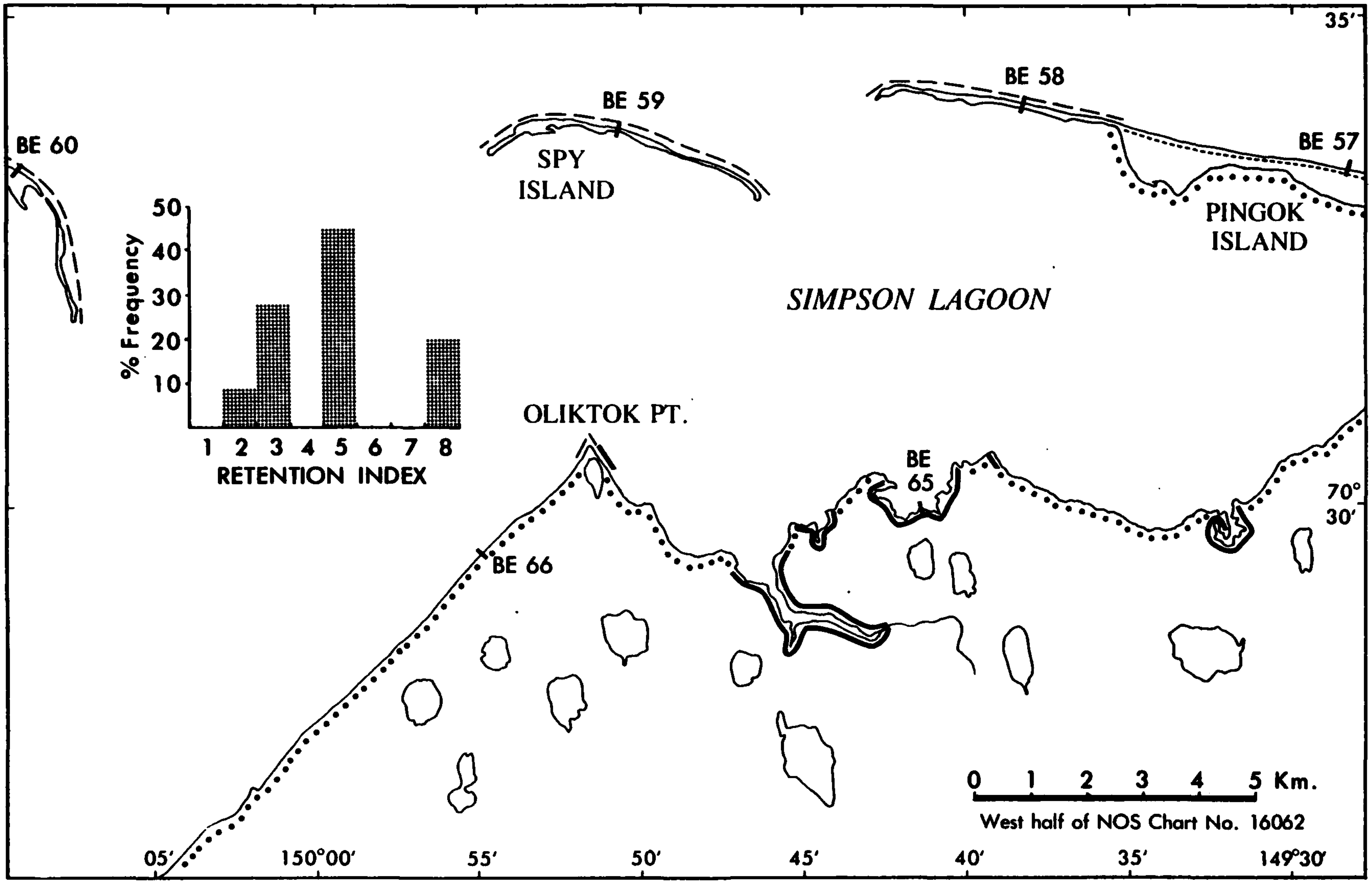

FIGURE 4.16 OLIKTOK POINT (149-30 TO 150-10W)

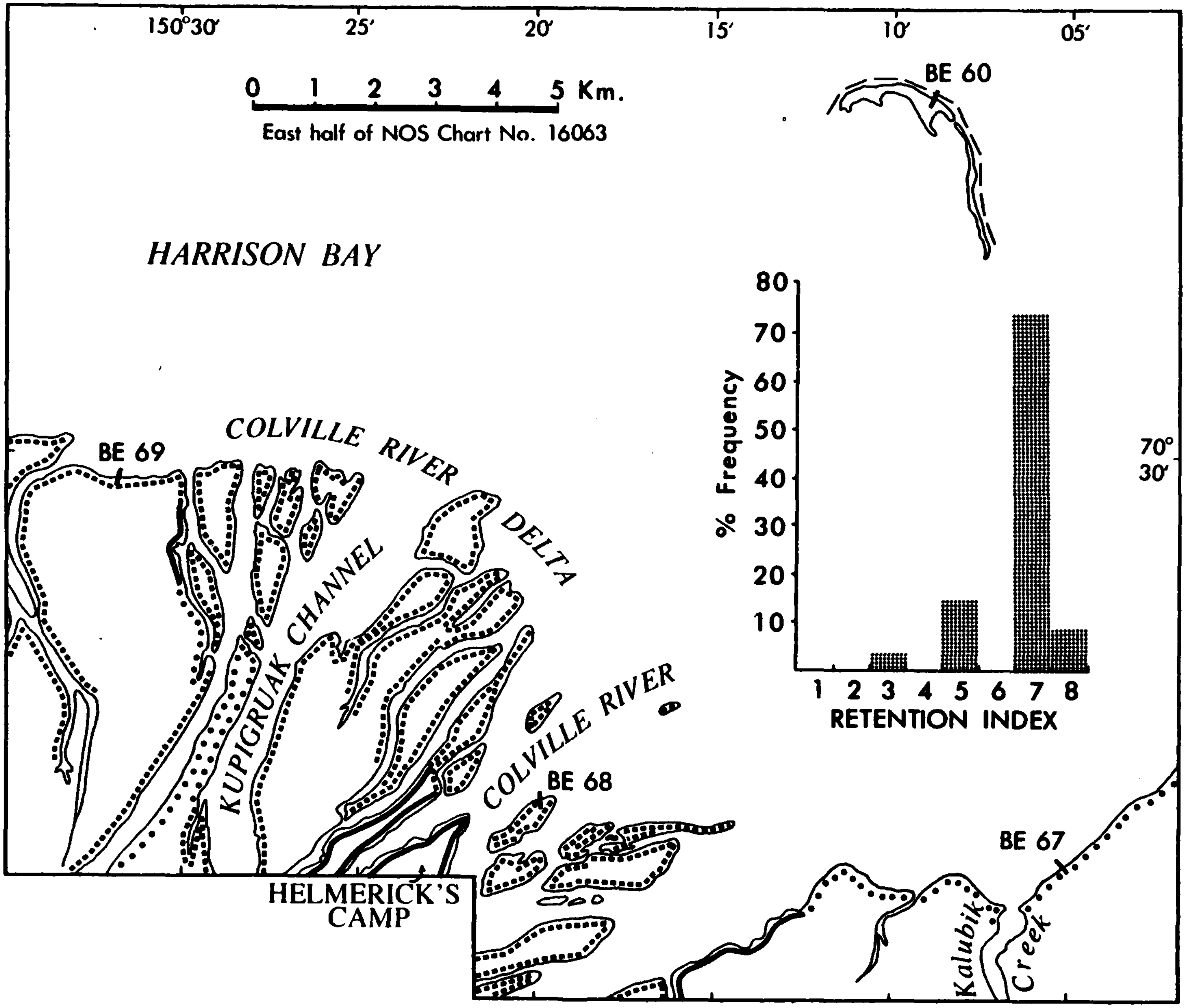

FIGURE 4.17 COLVILLE RIVER (150-05 TO 150-30W)

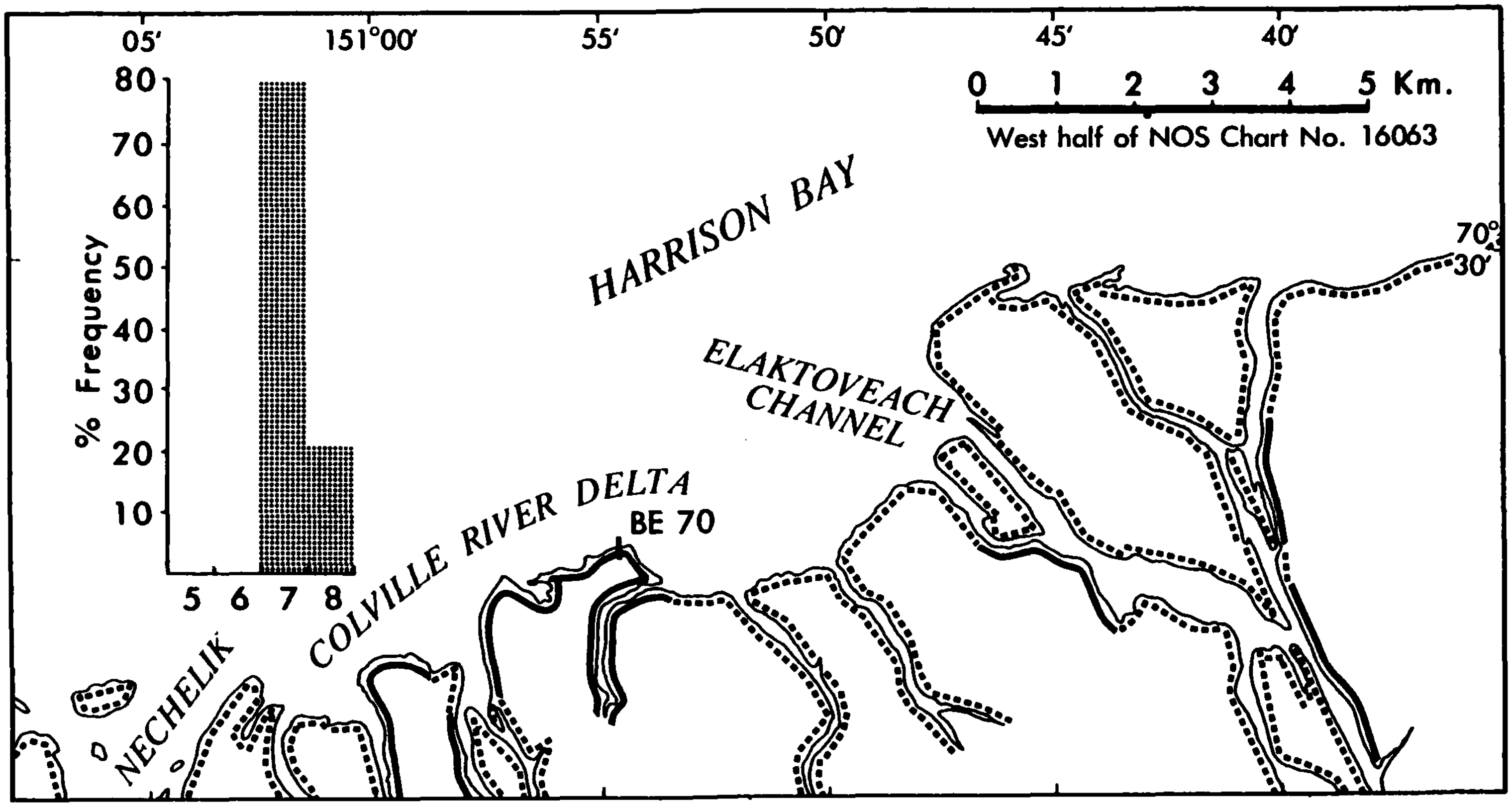

FIGURE 4.18 COLVILLE RIVER DELTA (150-35 TO 151-05W)

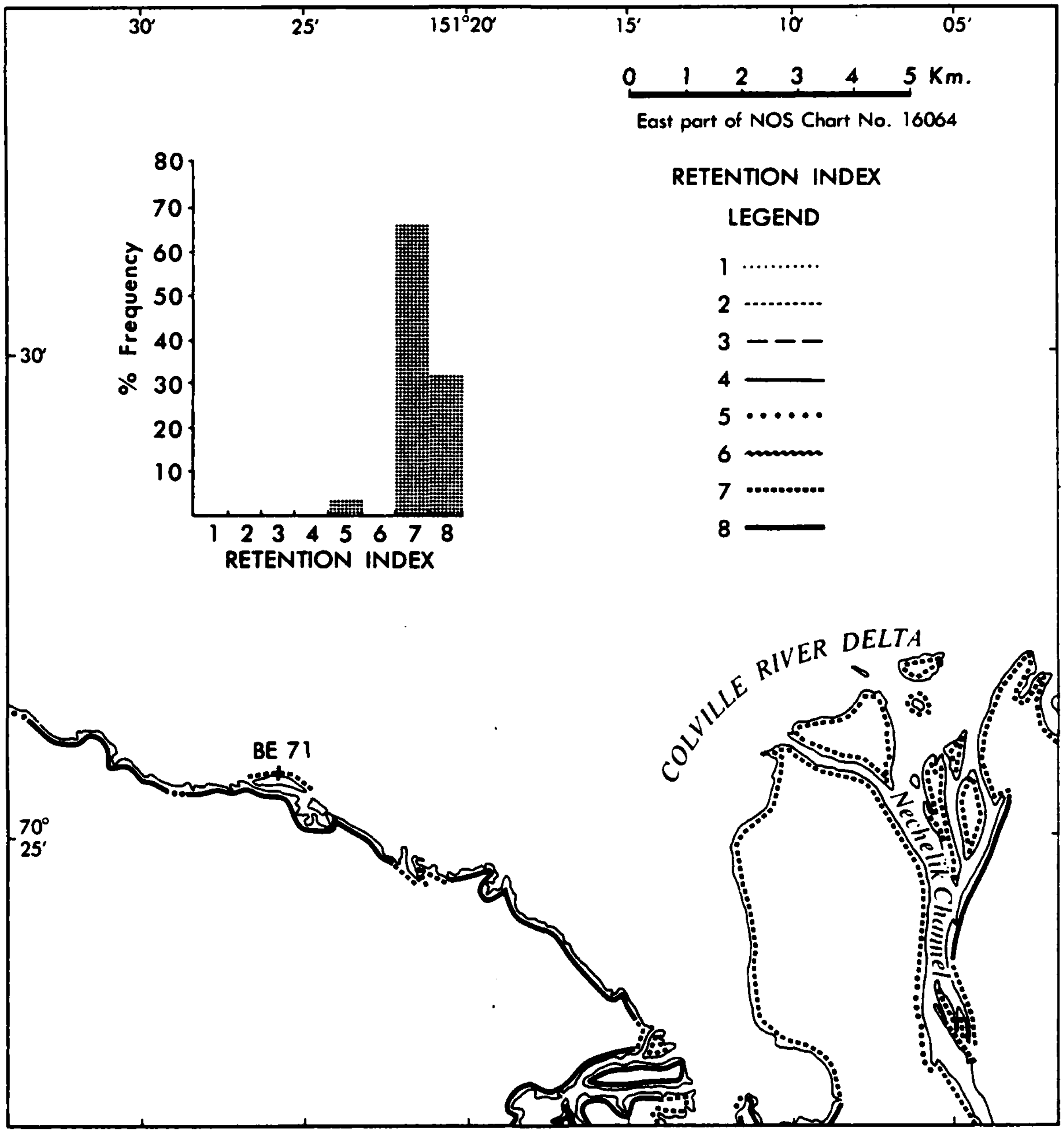

FIGURE 4.19 COLVILLE RIVER DELTA (151-05 TO 151-30W)

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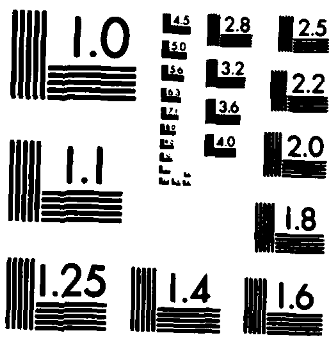
INC COLUMBIA MD R SCHULZE NOV 84 USCG-2-85
DTCG-39-84-R-00010

UNCLASSIFIED F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

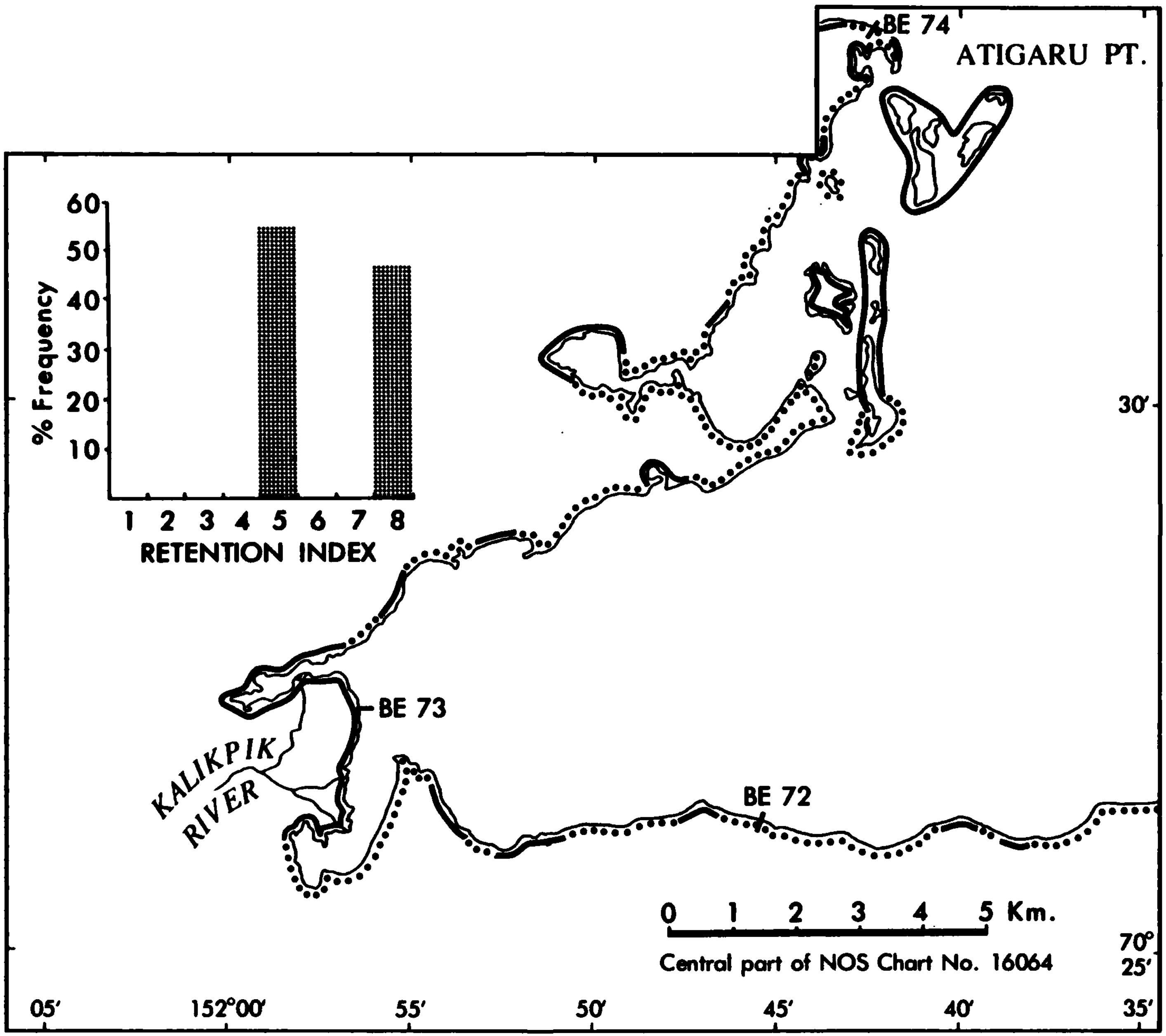


FIGURE 4.20 ATIGARU POINT (151-35 TO 152-05W)

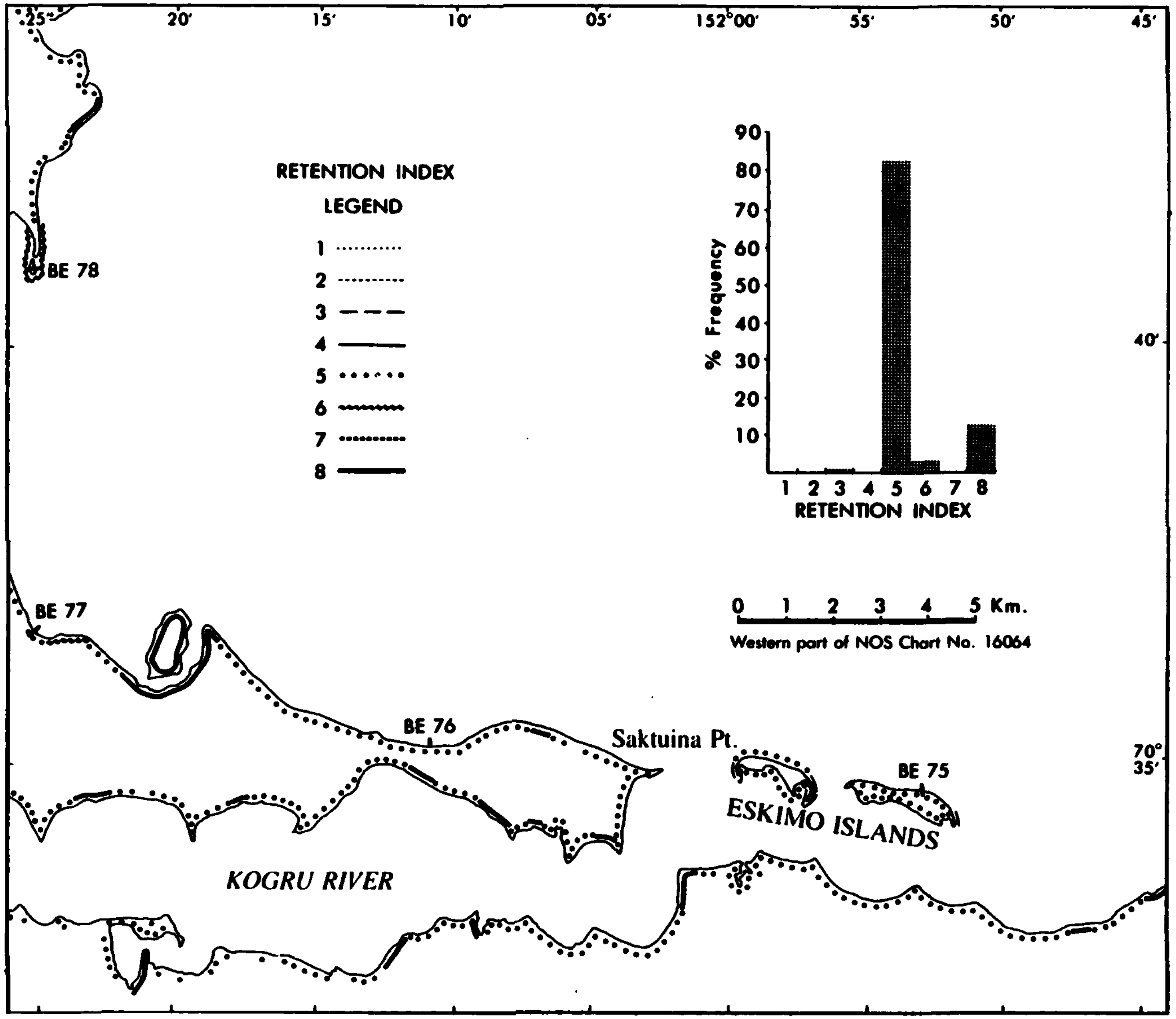


FIGURE 4.21 KOGRU RIVER (151-45 TO 152-20W)

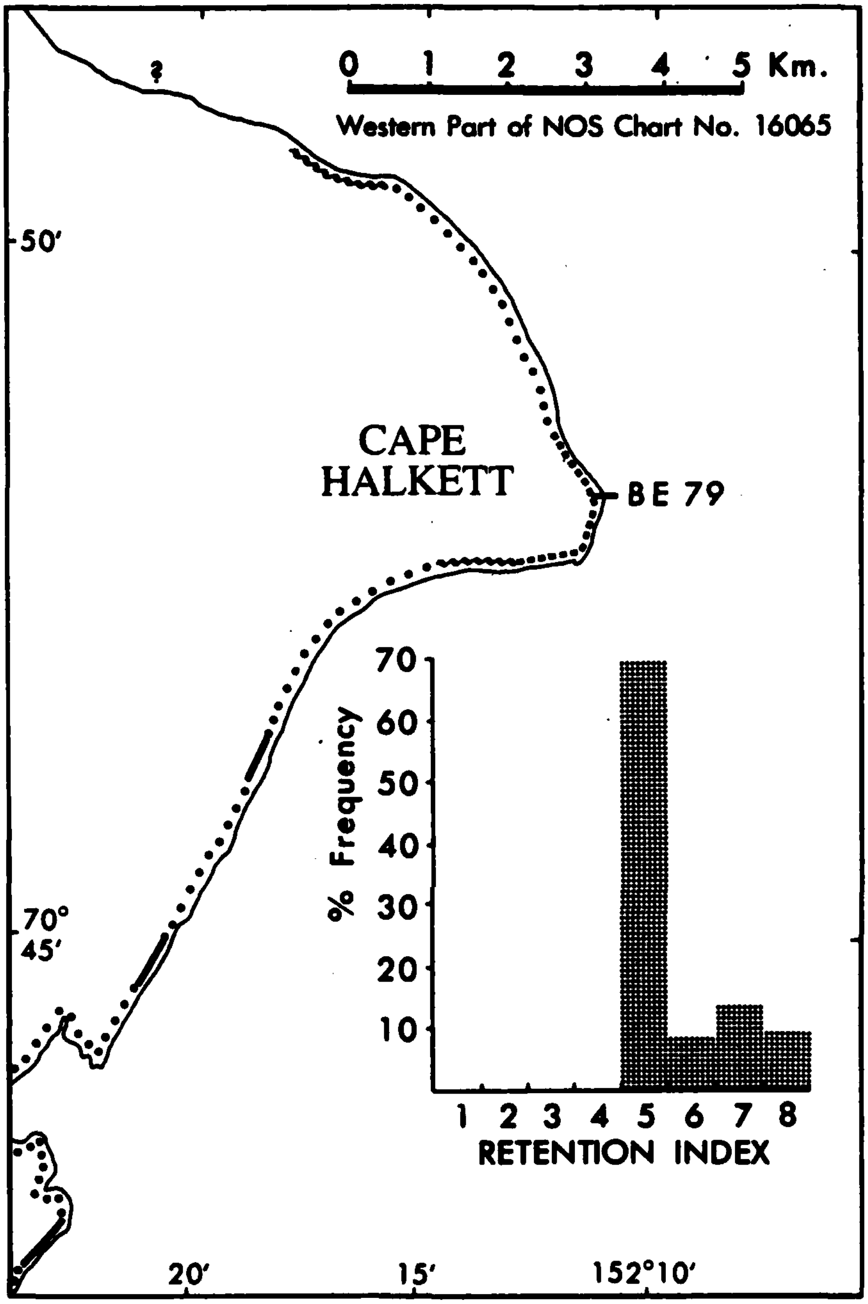


FIGURE 4.22 CAPE HALKETT (152-10 TO 152-25W)

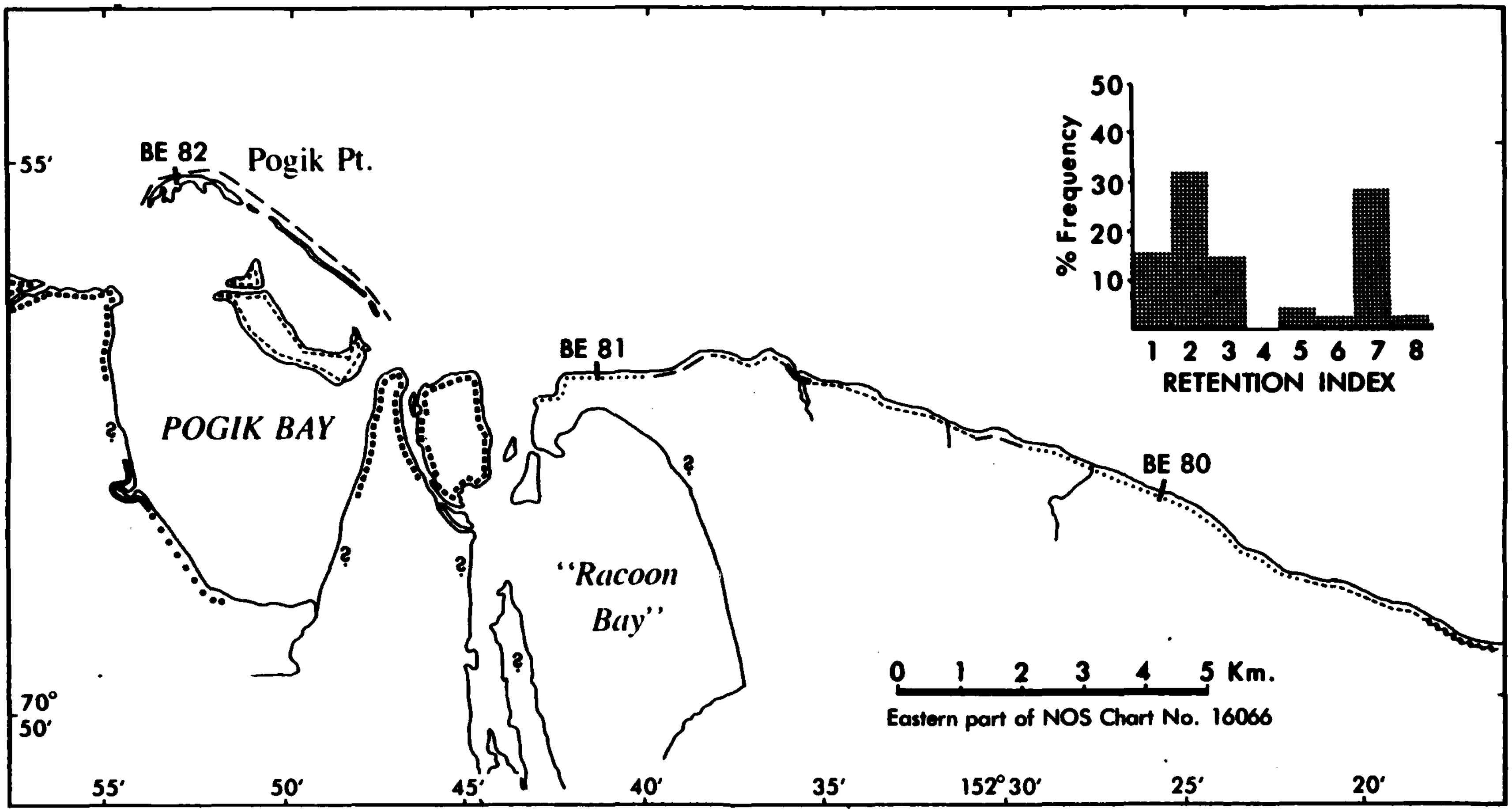


FIGURE 4.23 POGIK BAY (152-20 TO 152-55W)

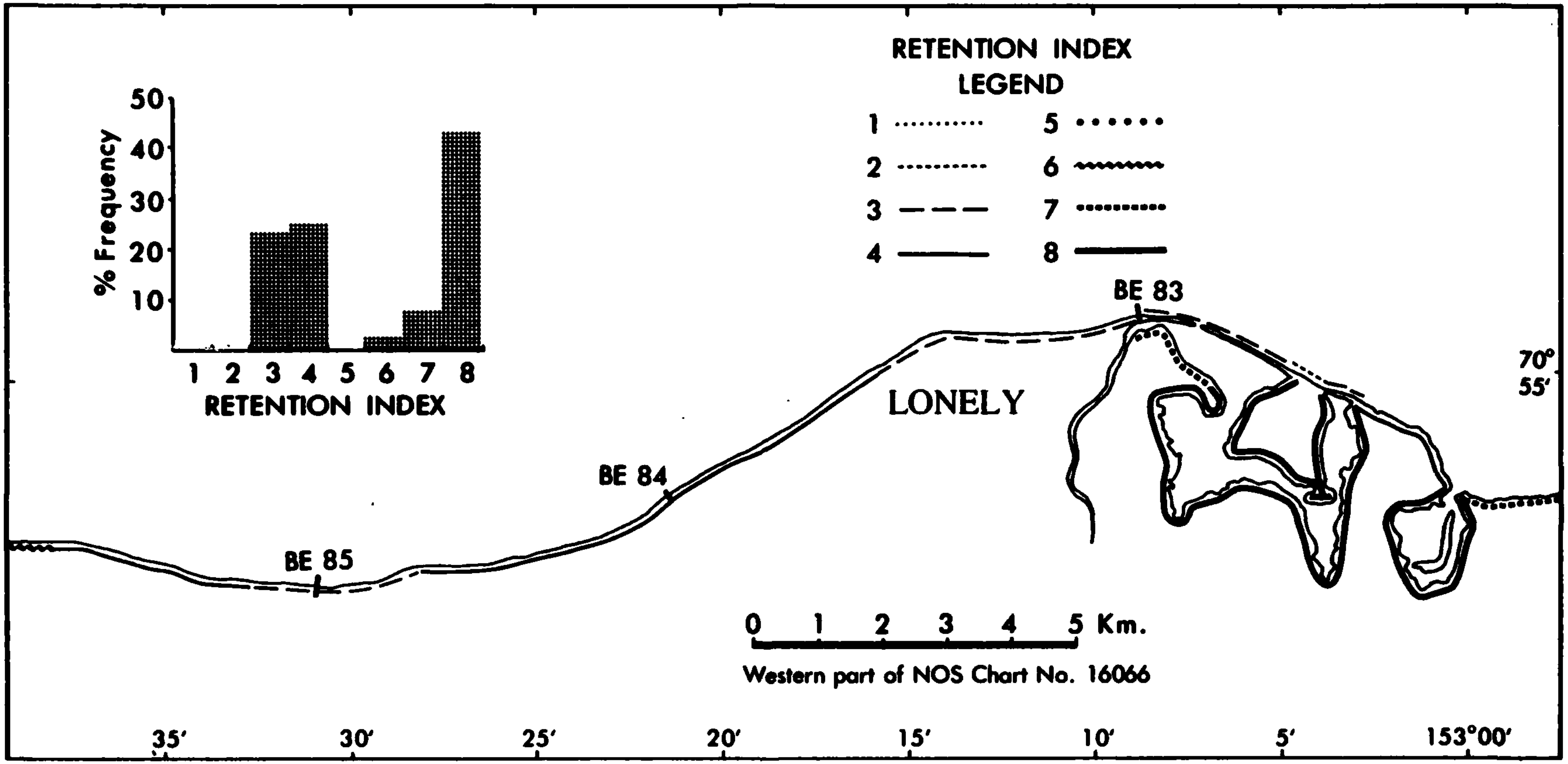


FIGURE 4.24 LONELY (153 TO 153-40W)

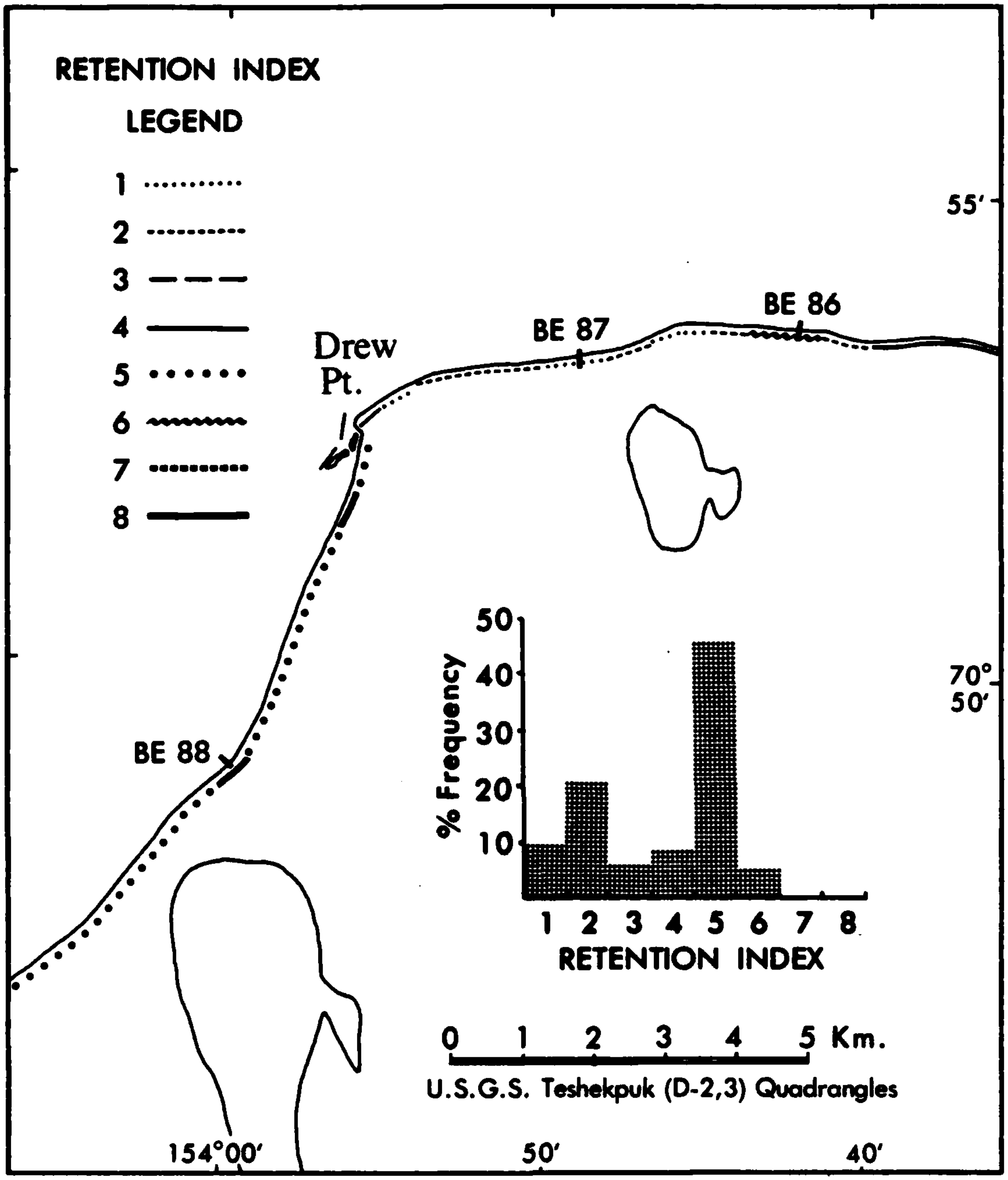


FIGURE 4.25 DREW POINT (153-40 TO 154-10W)

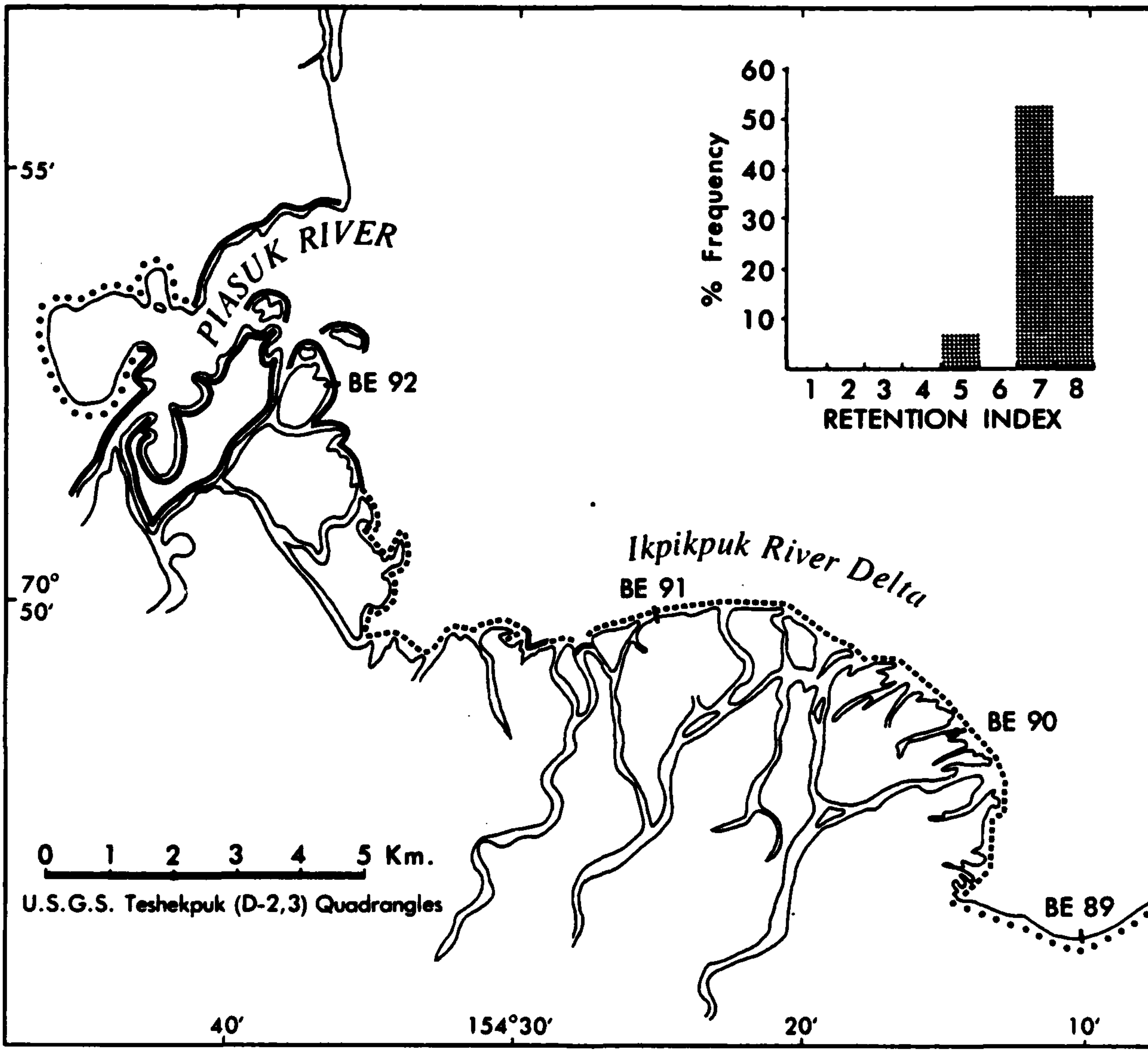


FIGURE 4.26 IKPIKPUK RIVER DELTA (154-10 TO 154-50W)

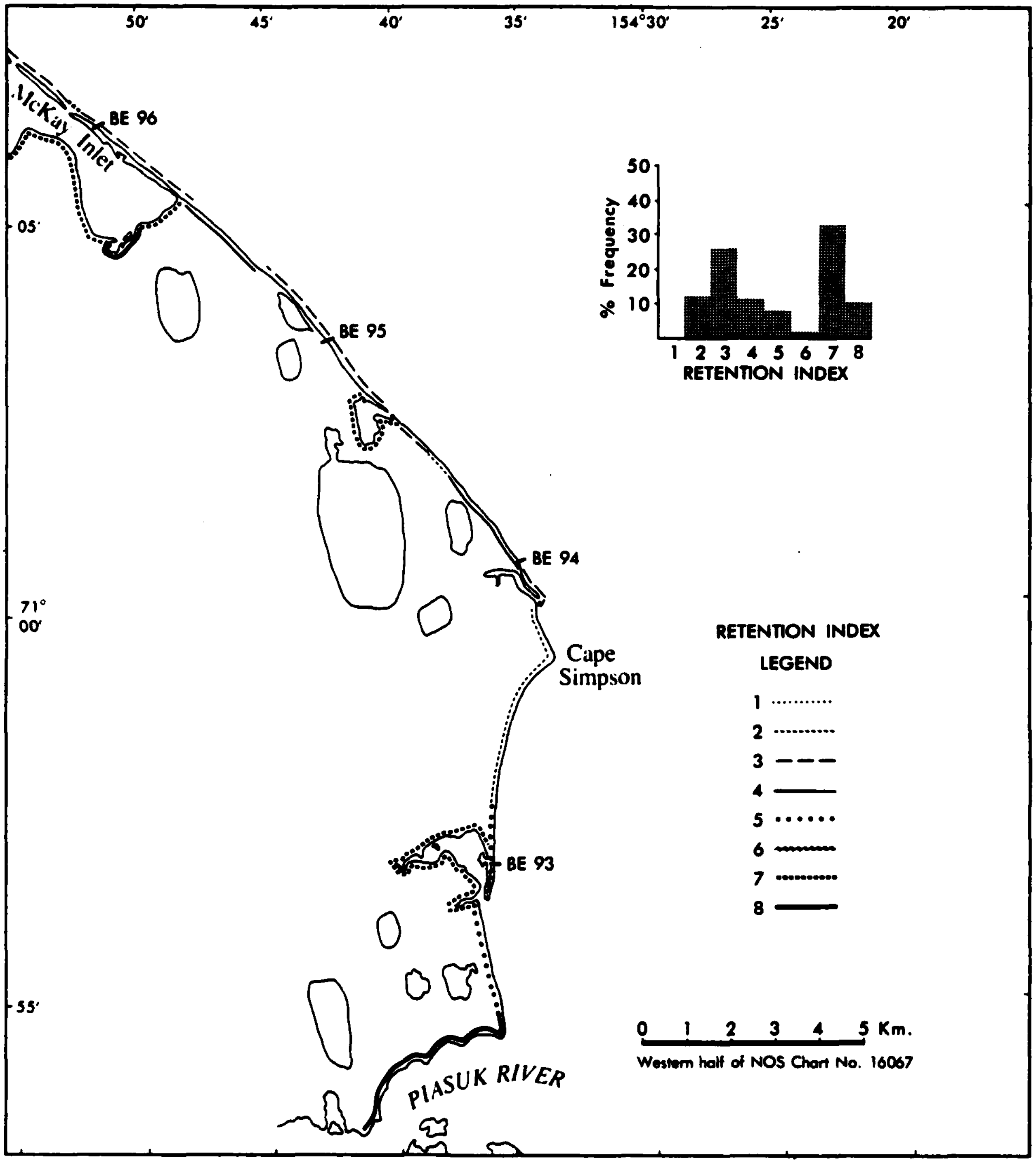


FIGURE 4.27 CAPE SIMPSON (154-20 TO 154-50W)

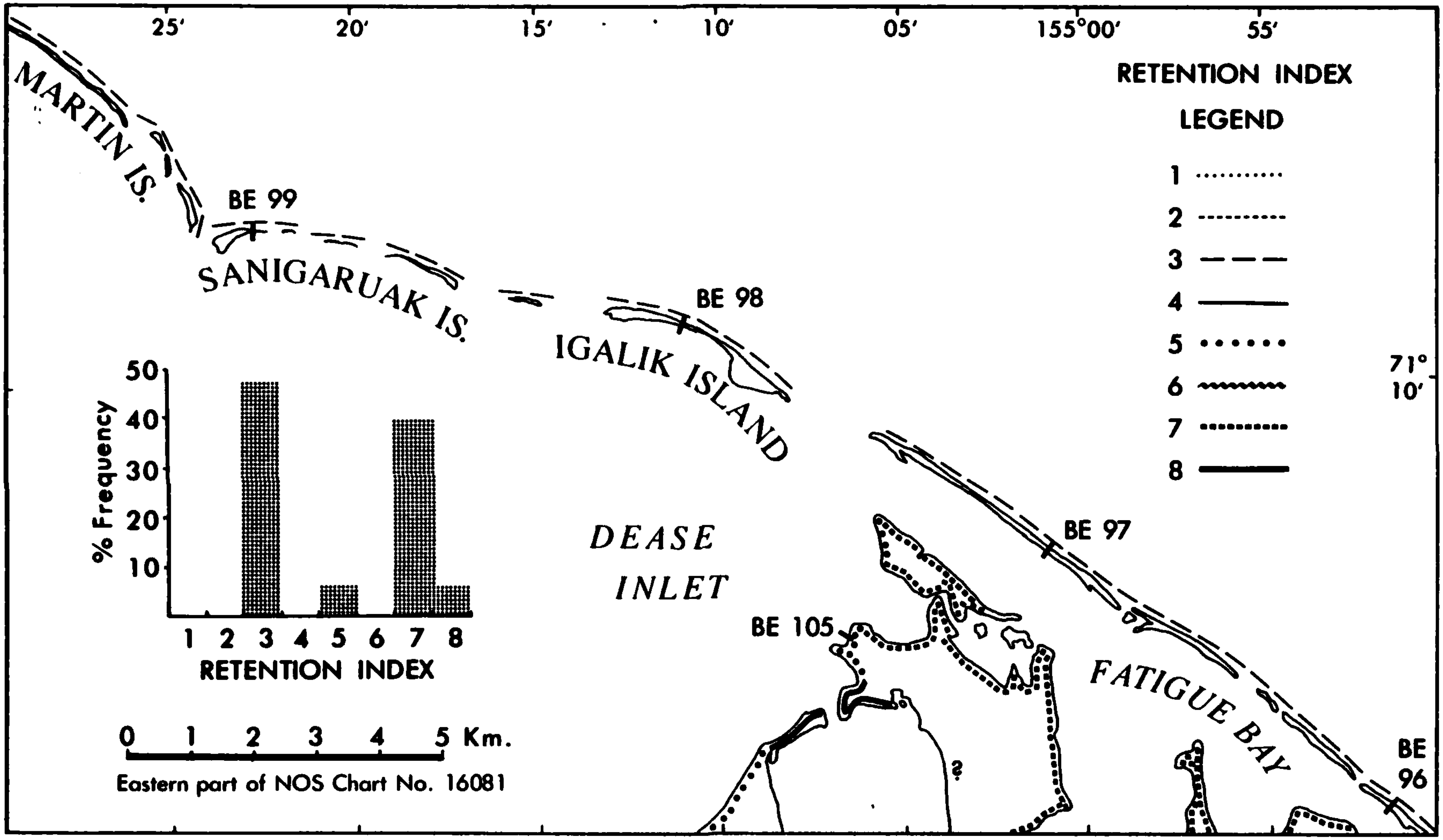


FIGURE 4.28 DEASE INLET (154-50 TO 155-30W)

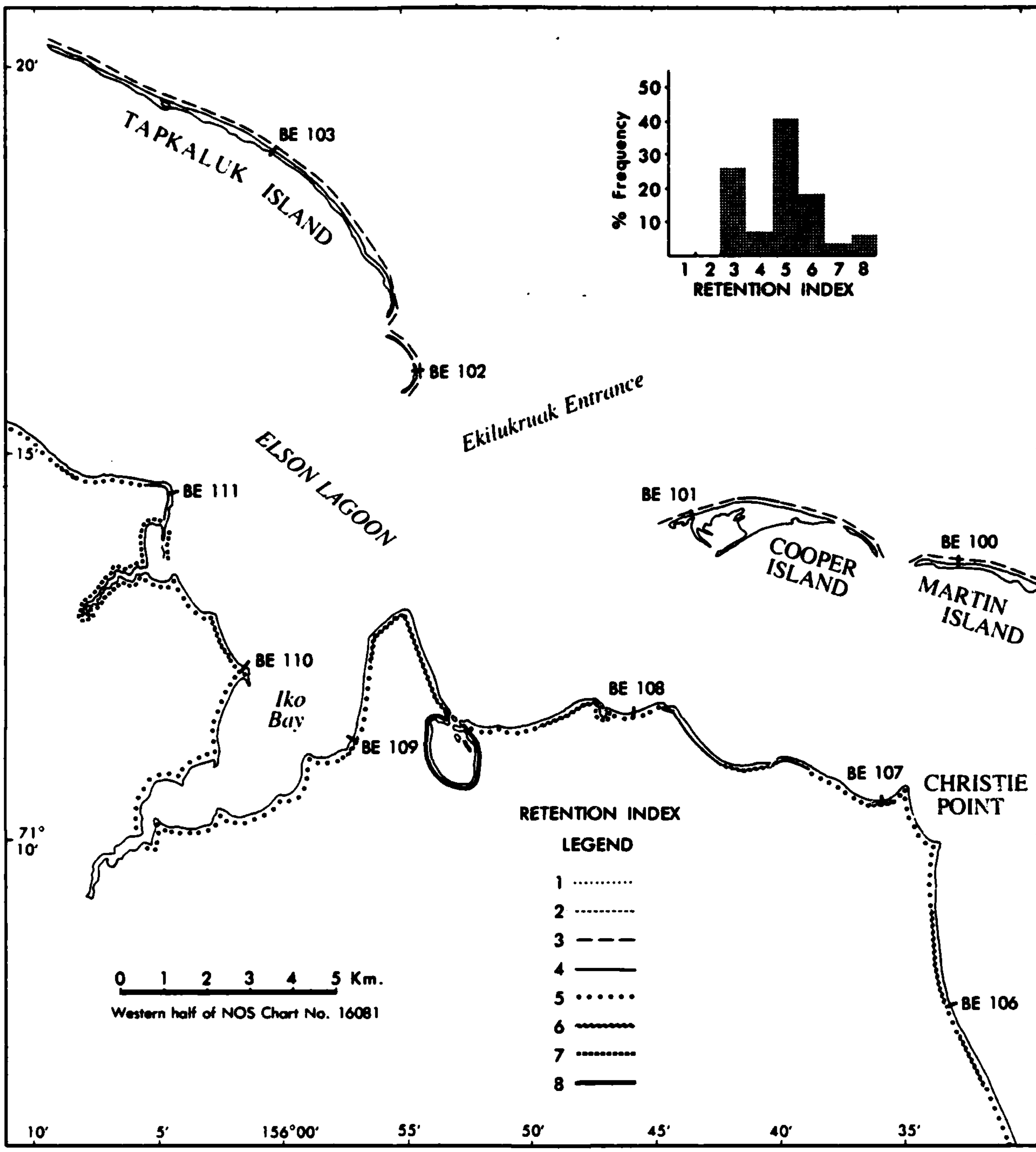


FIGURE 4.29 ELSON LAGOON (155-30 TO 156-10W)

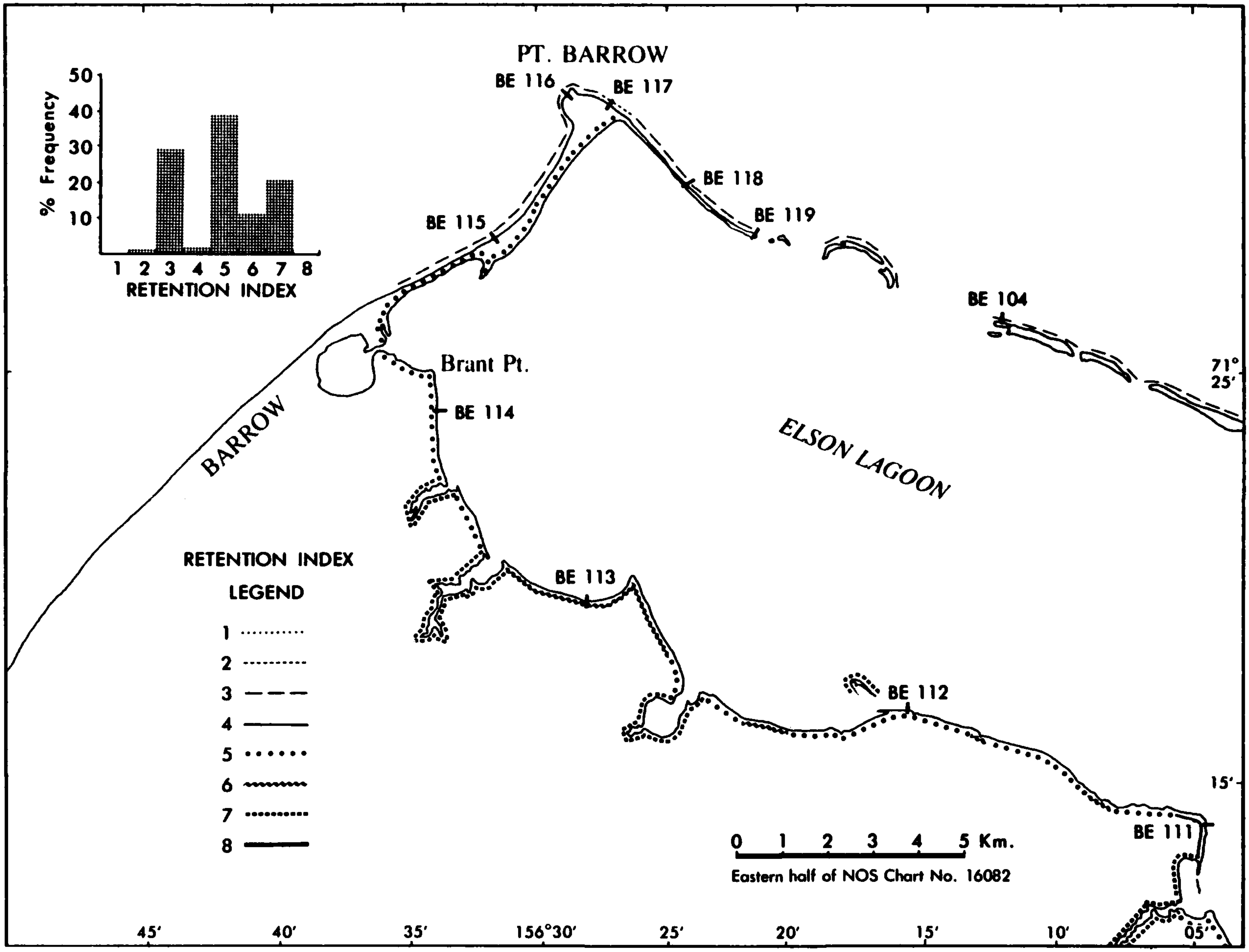


FIGURE 4.30 POINT BARROW (156-05 TO 156-50W)

SHORELINE INTERACTION REFERENCES

1. Gundlach, Erich R., Daniel D. Domeracki, and Larry C. Thebeau, Persistence of METULA Oil in the Strait of Magellan Six and One-Half Years After the Incident, Oil and Petroleum Pollution, Volume 1, Number 1, 1982.

2. Minister of Transport, Report of the Task Force Operation Oil, (Clean up of the ARROW oil spill in Chedabucto Bay), 1970.

3. U.S. Department of the Interior, Minerals Management Service, Final Environmental Impact Statement, Proposed Diapir Field Lease Offering (June1984), March 1984.

4. Nummedal, Dag, Persistence of Spilled Oil Along the Beaufort Sea Coast, Final Report for the National Oceanic and Atmospheric Administration Outer Continental Shelf Environmental Assessment Program Contract no. 03-5022-82, Research Unit 540, April, 1980.

5. Gunlach, E.R., M.O. Hayes, C.H. Ruby, L.G. Ward, A.E. Blount, I.A. Fischer , and R.J. Stein, Some Guidelines for Oil-Spill Control in Coastal Environments, Based on Field Studies of Four Oil Spills, "Chemical Dispersants for the Control of Oil Spills", (ASTM Specail Technical Publication 659), the report of a symposium sponsored by ASTM Committee F-20, 4-5 October 1977 in Williamsburg, Virginia.

5.0 SPILL SCENARIOS

5.1 Purpose of Scenarios

Six oil spill scenarios have been developed to illustrate how to use the Field Guide to solve practical spill behavior problems in the field. The scenarios have been kept relatively simple so that the details of a complex oil spill situation do not obscure the physcial problem of determining spill behavior. The scenarios selected illustrate typical kinds of spills that could occur offshore on the North Slope, but this list is by no means exhaustive. There are many other kinds of spills that could occur.

The scenarios were also selected to illustrate a variety of ice and environmental conditions. The scenarios selected do, in fact, cover a broad range of conditions, but they do not include all of the ice conditions and spill behavior situations that are described in the text. The scenarios describe how to apply the information that is presented in the text so that the reader should be able to use these methods to apply the information to other behavior situations.

The locations for the various scenarios were selected as typical places where the petroleum development activities described could occur. These locations are in no way intended to refer to any current or planned industry development plans. Further, selecting scenarios at these locations does not imply that development activities described are in any way hazardous or involve an unusually high risk of a spill.

Finally, the spill locations were not selected to illustrate spill types or spill locations that would be particularly hazardous to the environment. The scenarios were just selected to illustrate possible spill behavior situations. Also the spill behavior problems are extended to the point that the oil released reaches the shoreline, and when it does there is an evaluation of potential impact. Although this analysis is in every case purely objective and real, no effort was made to select scenarios or scenario locations that present a particularly high threat of environmental damage.

5.2 Overview of Selected Scenarios

The scenarios selected to illustrate typical spill behavior problems are as follows:

- o Open Water Spill - Arctic diesel is spilled during transfer from a barge to a gravel island during the first week of August.

- o Freeze-Up Spill - North Slope crude leaks from an undersea pipeline during the middle of October.

- o Winter Blowout Without Ignition - A well being drilled from a gravel island blows out of control in the middle of March.

- o Winter Blowout With Ignition - A well being drilled from a gravel island blows out of control in mid March. Early on the fourth day of the spill a decision is made to ignite the well.

- o Blowout Under Ice - A well being drilled through fast ice in mid March blows out of control.

- o Tanker Spill - A tanker collides with a supporting ice breaker and spills oil from two ruptured tanks during the first week in August.

5.3 Description of Work Sheets

A set of oil spill behavior work sheets has been developed to provide the OSC with an orderly method to record environmental conditions and predict oil spill behavior. This section describes the Work Sheets

required for each spill type and set of environmental conditions. The method of using these sheets to predict oil spill behavior is then demonstrated in a set of six typical arctic oil spill scenarios. The oil spill behavior problem is solved for each scenario using the appropriate Work Sheets. These scenarios illustrate the way the information in the Field Guide can be applied to real world problems. The paragraphs that follow list the Work Sheets and provide a detailed description of each line item data requirement. This description shows how the Work Sheets are used to predict oil spill behavior.

o Work Sheet #1: Initial Conditions. This sheet provides a format to record initial oil conditions at the time of the spill and environmental conditions at the spill site. Data entries include baseline oil properties that are available from records or can be measured plus environmental conditions that can be observed or recorded from available references.

o Work Sheet #2: Physical Properties After Weathering. This sheet provides a record of changes in oil properties that occur during the weathering process. These changes are obtained from curves in the Field Guide.

o Work Sheet #3: Oil Spill Budget. This sheet provides the format to record how much oil has been spilled according to slick thickness. These amounts can then be added to obtain a complete spill budget.

o Work Sheet #4: Spill Volume Remaining. This sheet provides a blank graph to display the volume of spill remaining data developed on Work Sheet 3.

o Work Sheet #5: Evaporation Rate. This sheet provides a graphical format to record percent of oil remaining for the first ten days of the spill. Information to draw these curves is obtained from the evaporation curves in Section 3.

o Work Sheet #6: Spreading on Open Water. This sheet lists data requirements needed to plot spreading on open water and to assess the spill impact on the shoreline.

o Work Sheet #7: Plot of Spill Drift. This sheet provides a maneuvering board format to compute spill drift.

o Work Sheet #8: Spreading in Ice. This sheet provides a format for describing oil spreading in broken ice, grease ice, pancake ice, rafted ice, rubble, and pressure ridges.

o Work Sheet #9: Spreading Under Ice. This sheet provides a format for describing oil movement under fast ice, under ice topography, uncer ice storage capacity, and large under ice features.

o Work Sheet #10: Spreading on Ice. This sheet provides a format to describe how oil spreads on ice and in snow.

o Work Sheet #11: Vertical Migration of Oil Through Ice. This sheet provides a format for describing how oil migrates up through thick, fast ice.

5.3.1 Description of Work Sheet Line Items

This section describes the information requirements and source of information for each entry on the Spill Behavior Work Sheets. The numbers correspond to the numbered items on the work sheets.

Work Sheet #1: Initial Conditions

INITIAL OIL CONDITIONS

Take a sample of spilled oil and measure physical properties if possible. This is desirable because North Slope crudes do not all have the same properties, and a spill from a pipeline may involve a mixture of several crudes. If it is not possible to measure physical properties, get them from the commercial producers or government regulatory agencies, such as the Department of the Interior Minerals Management Service.

1) Oil Temperature - Record the temperature of the oil as it enters the environment. For oil stored in tanks above ground, use the average ambient air temperature. For crude oil being produced by a well, use the well temperature.

2) Specific Gravity - Record the accepted specific gravity of the spilled product, corrected to initial temperature of the oil, if possible.

3) Viscosity - Record the viscosity of the spilled product corrected to the initial oil temperature.

4) Pour Point - Record initial pour point.

5) Solubility - Record the solubility at the initial oil temperature.

6) Slick Thickness - Record estimated slick thickness for the various spill environments as soon as possible. Record measured slick thickness as soon as it is available. Slick thickness may vary across the spill area, so space for four entries is provided. If there are more than four thicknesses, use another sheet.

7) Combustibility - Assess combustibility according to product type, slick thickness, and degree of weathering. A description of expected combustibility is contained in Section 2.7.

8) Emulsification - Estimate probability of emulsification based on the characteristics of the product spilled and the energy level in the spill area. Section 2.8 describes emulsification characteristics.

ENVIRONMENTAL CONDITIONS

9) Wind (Direction/Velocity, Kts) - Use measured wind force whenever possible. If wind observations are not available in remote areas, or if you wish to predict what will happen in the future, use average historical wind records. Average winds can be obtained from reference (1), Atlas of the Beaufort Sea.

10) Air Temperature - Use measured temperature when possible. For remote areas, average temperatures are available in reference (1).

11) Water Temperature - Lacking a better value, water is generally close to 0°C. In summer, higher-than-average temperatures may be slightly above 0°C, and as ice begins to form in the fall, surface temperature may drop to near -2°C. Seawater under ice is also close to -2°C. Average surface water temperatures are recorded in reference (1).

12) Ice Temperature - Ice temperature should be measured. Ice temperature can vary from 0°C to -20° or below in mid-winter. Ice temperatures may also vary locally. Average ice temperatures are not recorded in standard meterological publications.

13) Water Depth - Record water depth in meters, fathoms, or feet, depending on the charts available for the area. Nearshore depths can be found in reference (1).

14) Wave Height - Waves are generally slight. The average range

of wave height is recorded in reference (1).

15) Currents - Near shore currents are recorded in reference (1).

16) Tides - Tidal range is generally slight. Reference (1) contains a description of tidal conditions.

17) Storm Surges - Reference (1) shows height of storm surge above mean sea level for coastal areas and provides a method of predicting storm surges. Don't worry about storm surges unless weather conditions indicate that they can be expected.

18) Ice Conditions - Ice conditions are best observed at the spill site. Average ice condtions for remote areas can be obtained from reference (2).

19) Precipitation - Precipitation is observed at the spill site. Average precipitation conditions for each month are recorded in reference (1). Average conditions may be needed to predict oil weathering over a long period of time.

20) Visibility - Although visibility does not influence spill behavior, it may often affect spill response effectiveness. Average visibility conditions are recorded in reference (1).

21) Daylight - Use Figure 5.3.1 to estimate the number of hours of daylight and twilight.

Work Sheet #2: Physical Properties after Weathering

1) Day - This shows the time after the spill that the properties are recorded. Days 1 ,3, and 10 were selected because they show trends on the properties curves. Other time periods could also be used depending on the spill situation. Just write a new number in the day column and use additional data sheets if more points are needed.

2) Slick - Most spills leave highly irregular deposits, therefore there is not generally a single slick thickness. The work sheet has space for four slick thicknesses. If more spaces are needed, use additional forms.

3) Evaporation - Evaporation rates are determined from Figures 2.1.1 to 2.1.4 for Prudhoe Bay crude, and Figures 2.1.5 to 2.1.9 for arctic diesel. Note that the curves are for a wind envelope of 5 to 20 knots. Estimate one-third of the distance between these curves for each 5 knot difference in actual wind speed. For example, for 10 knots read percent oil remaining opposite a point 1/3 the distance between the 5 knot and the 20 knot curve. Work Sheet 3 provides a blank graph to plot percent oil remaining recorded in line 3. This will provide the OSC with a quick picture of how much oil is being lost to evaporation during the first 10 days after the spill.

4) Viscosity - Viscosity is only significant for the thicker accumulations of oil, therefore curves have not been plotted for the thin slicks. Figures 2.2.1 through 2.2.4 show viscosity for Prudhoe Bay crude and Figure 2.2.5 shows viscosity for arctic diesel.

5) Pour Point - Pour point is a general sort of characteristic that doesn't change much with the thickness of spill accumulation. Figure 2.3.1 shows pour point for Prudhoe Bay crude and Figure 2.3.2 pour point for arctic diesel.

6) Density - Figure 2.4.1 shows the density of Prudhoe Bay crude and Figure 2.4.2 shows the density of arctic diesel. As crudes weather they may have a density that is greater than sea ice (about 0.92g/cc) and

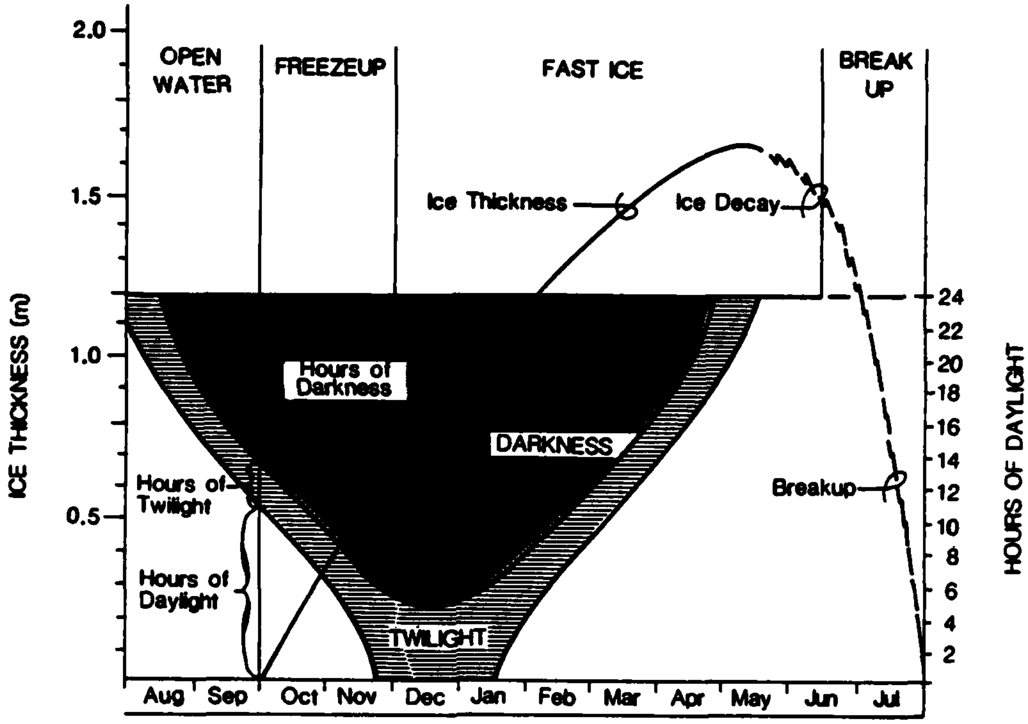


FIGURE 5.3.1 HOURS OF DAYLIGHT AND FAST ICE THICKNESS

can be easily swept under the ice. If particles of spilled crude become attached to sediments, the density may become greater than sea water (about 1.025 g/cc) and the spill may sink.

7) <u>Solubility</u> - Figure 2.5.1 shows the solubility of Prudhoe Bay crude and Figure 2.5.2 shows the solubility of arctic diesel. No detectable amount of the spill will be lost because of dissolution, however it could have some effect on organisms in the water.

<u>Work Sheet #3: Oil Spill Budget</u>

This Work Sheet provides a place to compute and record the volume of oil that has been spilled in terms of slick thickness, slick location, and estimated area covered. These results can be added to show the total amount of oil in each spill thickness category. A space is also provided to record the percent of oil remaining based on the evaporation curves. The percent remaining can be used to estimate the amount of oil that remains on days that the spill areas and slick thicknesses cannot be measured. Each Work Sheet has space to record spill volume for four slick thicknesses. If there are more characteristic thicknesses or more areas to record information, use additional sheets.

Work Sheet #4: Spill Volume Remaining

This Work Sheet provides a blank graph to plot the data developed on Work Sheet 3. Two cycle semi-log paper is used to permit plotting a wide variety of spill sizes. Units on the vertical axis can be in cubic meters, barrels, or gallons depending of the spill size and situation. The scale of the vertical axis has also been left blank so that it can be adjusted for spill size. For example, if the base of the vertical axis is 1 unit, the next cycle should be labeled 10 units and the top space 100 units. Similarly, if the base of the vertical axis is 10 units, then the next cycle is 100 units and the top space is 1000 units, and so forth. This permits the user to adjust the scale of the plot to accommodate a wide variety of spill situations.

The horizontal scale is linear and is labeled in days. This scale could also be used as hours or it could be doubled to twice the number of days for a long term plot.

For these scenarios, the volume remaining will only be affected by natural processes, mostly evaporation. In a spill situation the volume remaining could also be adjusted to reflect spill recovery. In this case the plot would show both the results of natural losses and the effectiveness of the spill response effort.

Work Sheet #5: Evaporation Rate

This Work Sheet provides a blank graph to plot percent of oil remaining for the first ten days of the spill. The horizontal time axis could also be plotted as hours after the spill, or the scale could be doubled to continue the plot for a longer time after the spill.

Work Sheet #6: Spreading on Open Water

1) Spill Radius - Use Figures 3.1.1 through 3.1.4 for thick slick/radius estimate for the standard spill sizes appearing on the graphs. Use Figure 3.1.5 to estimate spill radius if the slick thickness can be measured and volume of oil spilled is known. Figure 3.1.5 can also be used to determine volume of oil spilled if both the spill radius and slick thickness can be measured.

2) Slick Thickness - Measure slick thickness if possible. If not estimate slick thickness based on spill behavior described in Section 3.

3) Spill Drift Vector - The description of Work Sheet 7 provides instructions for determining the spill drift vector.

4) Distance to Shoreline - Measure distance from a hydrographic chart if possible. Time to reach shoreline is distance to shoreline divided by the spill drift velocity. Measure the minimum distance to the shoreline. Depending on the terrain, this may be the site selected to establish a base camp for the response effort. Also measure the distance to the closest land in the range of directions of possible spill drift vectors. Then measure the distance to land to the farthest point oil might come ashore within the range of possible spill drift vectors.

5) Estimated Time of Arrival at Shoreline - Time of spill plus time to reach shoreline.

6) Length of Shoreline Contaminated - The length of shoreline contaminated can be measured according to Spill Retenion Index using the charts provided in Section 4. Note that the assessment of impact is different for each Spill Retention Index. If you know the length of shoreline contaminated, you can also record how much is in each spill

retention index category. This provides a preliminary assessment of possible spill impact.

7) <u>Distance to Pack Ice</u> - Measure the distance to pack ice if possible. Reference (2) can be used for remote areas or to predict the likely future location of the pack ice.

8) <u>Estimated Time of Arrival at Pack Ice</u> - Use spill drift vector and distance to pack ice to determine the time of arrival.

9) <u>Length of Pack Ice Contaminated</u> - Use vectors showing the range of the spill drift and consider how a current may move the oil along the edge of the ice.

10) <u>Estimated Drift of Pack Ice</u> - Table 5.4.1 shows the average monthly drift of the pack ice in nautical miles per day.

current for the area given in reference (1). There are two current vectors provided in reference (1), one for average winds and one for unusual winds. Be sure to use the current vector corresponding to typical winds at the time of the spill. Winds and currents are recorded on Work Sheet 1. Add current drift and wind drift vectorially on Work Sheet 7 to determine the resultant spill drift. Plot current drift first because current is likely to be fairly constant for a given location. The spill will move at full current velocity in the direction the current is moving. The spill will only move at about 3% of the wind velocity. Remember that wind direction is the direction <u>from which</u> the wind is coming. The spill will move in the opposite direction (wind direction + 180°). Since wind direction and velocity are highly variable, you may wish to plot the range of wind directions and velocities at the end of the current vector

TABLE 5.4.1 AVERAGE MONTHLY ICE DRIFT SPEED
(NAUTICAL MILES/DAY) (1)*

LATITUDE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
71-72N				1.4	2.8	5.6	6.5	6.1	6.1			
72-73N				2.3	3.3	3.7	5.1	3.3	3.3	4.2	4.2	5.1
73-74N	5.6	2.3	1.9	1.9	2.8	2.8	3.7	4.7	9.3	6.1	6.1	4.2
MONTHLY AVERAGE	5.6	2.3	1.9	1.9	2.8	3.7	5.1	4.7	6.1	5.1	5.1	4.7

*Speed converted from cm/sec to nm/day.

<u>Work Sheet #7: Plot of Spill Drift</u>

For open water, the spill drift vector is a combination of wind drift and current drift. If the current cannot be measured, use the average to determine the <u>range</u> of possible drift at the spill. Scenario I shows how to plot the range of spill drift.

Work Sheet #8: Spreading on Ice

The behavior of spilled oil moving in ice can be developed from the description provided in Section 3.0 of the text.

Spreading in broken ice is described in Section 3.3. Spreading in grease ice and pancake ice is described in Section 3.3.3. Spreading in rafted ice, rubble fields, and in pressure ridges is described in Section 3.3.4.

Work Sheet #9: Spreading Under Ice

The behavior of oil spreading under ice can be developed from Section 3.4. Spill behavior under ice is covered in Section 3.4.1 and movement with currents under ice is covered in Section 3.4.5. Under ice topography is described in Section 3.4.2, under ice storage capacity in Section 3.4.3, and large (special) under ice features are described in Section 3.4.4.

Work Sheet #10: Spreading on Ice

Section 3.5 describes oil spreading on ice and snow. Spreading on winter ice is described in Section 3.5.2, and spreading on summer ice is in Section 3.5.3. Figure 3.5.1 provides an estimate of the radius of spill on ice for a variety of spill sizes and Figure 3.5.2 shows an estimate of spill radius for varying degrees of surface roughness.

Section 3.5.4 describes oil spreading on snow. Figure 3.5.3 provides an estimate of the absorption capacity of snow.

Work Sheet #11: Vertical Migration of Oil Through Ice

1) Beginning of Migration - Note brine channel development in the field to estimate when vertical migration will begin.

2) Rate of Migration - Figures 3.7.2 and 3.7.3 show possible rates of vertical migration based on field tests.

3) Behavior on Surface - The behavior of the oil that has surfaced during breakup is described in Section 3.7.3.

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS

DATE AND TIME SPILL BEGAN ______________________________

SPILL LOCATION ____________________ TYPE OIL ______________

AMOUNT SPILLED ______________________________

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) ____________ 2) SP. GRAVITY (g/cc) ____________

3) VISCOSITY (cp) ________ 4) POUR POINT (°C) ________ 5) SOLUBILITY ______

6) SLICK THICKNESS (1) ____________ (3) ____________
(2) ____________ (4) ____________

7) COMBUSTIBILITY ______________________________

____

____

____

8) EMULSIFICATION ______________________________

____

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) ______________________________

____

10) TEMPERATURE (°C): AIR ________ 11) WATER ________ 12) ICE ______

13) WATER DEPTH (m) ________ 14) WAVE HEIGHT (m) ________ 15) CURRENTS ______

16) TIDE (m) ____________ 17) STORM SURGE HEIGHT ABOVE MSL (m) ________

18) ICE CONDITIONS ______________________________

____

____

____

____

____

19) PRECIPITATION ______________________________

____

20) VISIBILITY ____________________ 21) DAYLIGHT (HRS) ____________

SPILL BEHAVIOR WORK SHEET #2

PHYSICAL PROPERTIES AFTER WEATHERING

1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)												
4) VISCOSITY (cps)												
5) POUR POINT (°C)												
6) DENSITY (g/cc)												
7) SOLUBILITY (g/m3)												

REMARKS: ______________________________

____

____

SPILL BEHAVIOR WORK SHEET #3
OIL SPILL BUDGET

Day ___________

Location	Thickness	Area	%Remaining	Volume

Day ___________

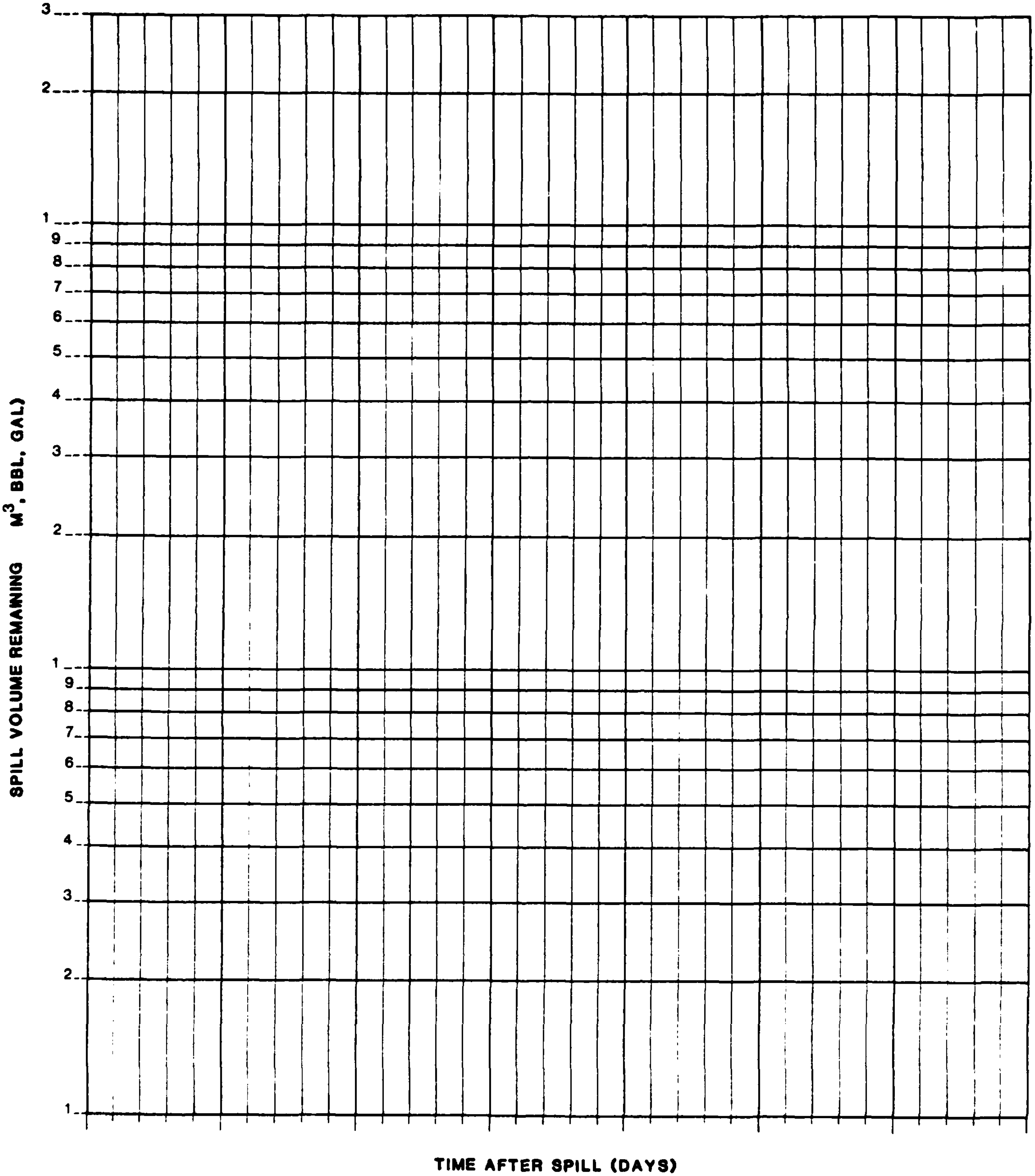
Location	Thickness	Area	%Remaining	Volume

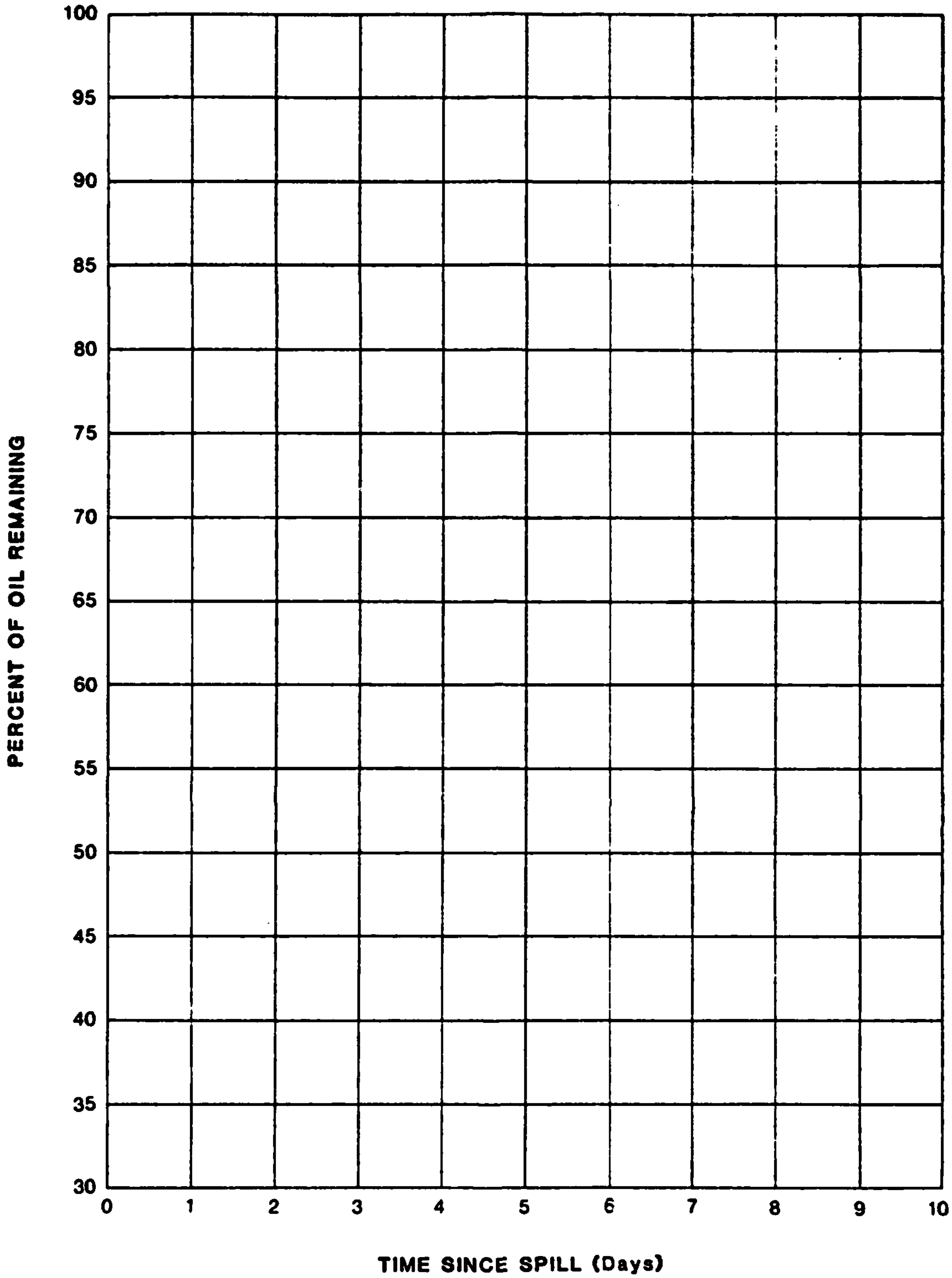
Day ___________

Location	Thickness	Area	%Remaining	Volume

SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING





SPILL BEHAVIOR WORK SHEET #5

EVAPORATION RATE

SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER

	THICK SLICK	THIN SLICK
1) SPILL RADIUS (m):	____________	____________
2) SLICK THICKNESS (mm):	____________	____________

3) SPILL DRIFT VECTOR: AVERAGE ____________ RANGE ____________

4) DISTANCE TO SHORELINE (NM): MAX ____________ MIN ____________

TIME TO REACH SHORELINE (HRS): MAX ____________ MIN ____________

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST________LATEST________

6) LENGTH OF SHORELINE CONTAMINATED (NM): ____________

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1 ________	5 ________
2 ________	6 ________
3 ________	7 ________
4 ________	8 ________

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- SHORELINE TYPE ____________
- IMPACT ____________
- PERSISTENCE ____________
- PROTECTION ____________
- CLEAN-UP ____________

7) DISTANCE TO PACK ICE (NM): ________ TIME TO REACH PACK ICE(HRS) MAX______ MIN______

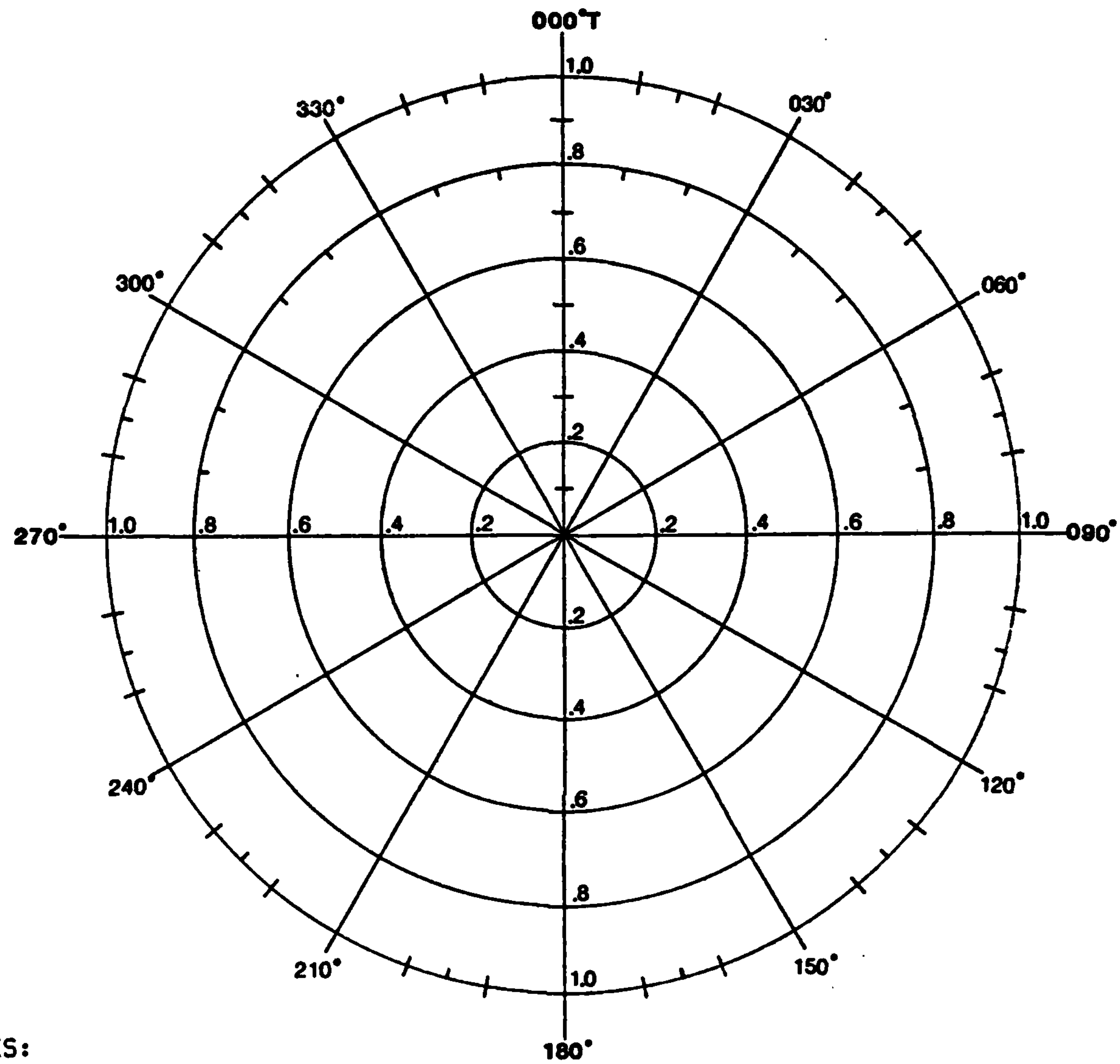
8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST ______ LATEST ________

9) LENGTH OF PACK ICE CONTAMINATED (NM) ____________

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) ____________

SPILL BEHAVIOR WORK SHEET #7

PLOT OF SPILL DRIFT



NOTES:

1. The compass rose is marked for each 10° true drift.

2. Because current drift is likely to be low in the Arctic, the velocity scale is 0 to 1 knots. If currents are higher, the scale can be doubled or even multiplied by a factor of 10.

3. Plot current drift from the center in the estimated direction of drift and at the estimated velocity. Next align a straight edge at the center of the circle in the direction the wind is blowing. Slide the ruler parallel to this direction out to the end of the current vector and draw the wind vector at 3% of the wind velocity. Draw a vector from the center of the circle to the end of the wind vector. This is the resultant spill drift.

4. Now determine the range of spill drift. Draw two vectors representing the extremes of wind direction and velocity for current conditions from the end of the current vector. Draw two more vectors from the center of the circle to the ends of the new wind vectors. These two new vectors represent the range of likely spill movement.

SPILL BEHAVIOR WORK SHEET #8
SPREADING IN ICE

SPREADING IN BROKEN ICE

1) SPREADING IN/AGAINST BROKEN ICE

2) SPREADING IN GREASE & PANCAKE ICE

3) SPREADING IN RAFTED ICE

4) SPREADING IN RUBBLE & PRESSURE RIDGES

SPILL BEHAVIOR WORK SHEET #9
SPREADING UNDER ICE

1) MOVEMENT UNDER FAST ICE

2) UNDER ICE TOPOGRAPHY

3) UNDER ICE STORAGE CAPACITY

4) LARGE UNDER ICE FEATURES

SPILL BEHAVIOR WORK SHEET #10
SPREADING ON ICE

1) SPREADING ON WINTER ICE

2) SPREADING ON SUMMER ICE

3) SPREADING ON SNOW

SPILL BEHAVIOR WORK SHEET #11
VERTICAL MIGRATION OF OIL THROUGH ICE

1) BEGINNING OF MIGRATION

2) RATE OF MIGRATION

3) BEHAVIOR ON SURFACE

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5.4 Oil Spill Scenarios

This section contains a set of six oil spill scenarios that have been selected to illustrate possible spill conditions and typical environmental conditions. The scenarios show how to use Work Sheets to describe and to solve oil spill behavior problems. Since each data entry for the Work Sheets is described in the preceeding section, this section only mentions the specific or unusual requirements for each scenario.

5.4.1 SCENARIO I - OPEN WATER

Arctic diesel is spilled during transfer from a barge to a gravel island at 1400 local time on 1 August. Figure 5.4.1 shows the transfer configuration.

Spill Location: A hypothetical gravel island in the vicinity of 70-30N, 148-35W, about 5 nm east-northeast of the north end of Long Island. Figure 5.4.2 shows the location.

Season: Open water, first week in August.

Spill Description: During the fuel transfer, a weld in the onshore fuel tank fails, allowing diesel fuel to pour out of the tank. The tank is surrounded by an impermeable dike; however, the oil escapes the dike and fuel flows through the gravel and enters the water. Fuel continues to pour from the tank until the liquid level drops below the failed seam. In this case 20,000 gallons of arctic diesel are released into the water. When the accident is reported, the barge crewman immediately shuts off the flow to the tank and secures the barge pumping system.

Most of the oil escapes into the water; however, in some places away from the main source of the spill the oil coats the gravel with a thickness of about 0.1 mm, and in other locations there are 5 and 10 mm pools of oil. The oil that escapes into the water spreads to a thin film of oil surrounded by a sheen.

Development of Work Sheet Entries

Work Sheet #1: Initial Conditions

This section tells where you can find the necessary information and how to make calculations and estimates.

For initial conditions, record the known physical μ operties of the oil. If the oil temperature is not known and the oil is stored in a tank above ground, use the average ambient air temperature. The other items in initial conditions, i.e., viscosity, pour point, and solubility, should come from oil company records. Record an observed slick thickness if possible. For this scenario it is assumed that there is a thicker slick with a thickness of 0.1 mm surrounded by a thinner slick of about 5 microns (.005 mm). It is also assumed that there are pools of oil on the pad 5 mm and 10 mm deep. The depth of the oil pools should be measured.

Environmental conditions should be measured at the spill site. Average conditions from historical records can be used for planning purposes, however, measured conditions are best for making computations and estimates. For this scenario environmental conditions are average values for the area from reference (1). The current is in the direction that would occur from prevailing easterly winds. Figure 5.3.1 shows hours of daylight for each month and fast ice thickness.

Work Sheet #2: Physical Properties After Weathering

The physical properties are

recorded for days 1, 3, and 10 because these times provide points that best describe the weathering envelope. For this scenario, slicks 1, 2, 3, and 4 correspond to a slick thickness of 0.005 mm, 0.1 mm, 5 mm, and 10 mm as shown in item 6 of Work Sheet 1. The evaporation history of each slick is determined from Figures 2.1.5 to 2.1.8 and is recorded in item 3 of Work Sheet 2. Evaporation represents the most significant loss of spilled oil to the environment. To get a better idea of how the evaporation occurs, plot these points for days 1, 3, or 10 on the blank graph provided on Work Sheet 5. Since only three points are plotted for each slick, the curves are not rounded out to show the full extent of the evaporation. For example, additional points plotted between days 3 and day 10 would round out the curve and show a slightly higher rate of evaporation than the straight line graph.

Items 4 through 7 of Work Sheet 2 have less significance for arctic diesel than for heavier products. Viscosity and pour point remain very low, even after weathering. Density is also low. This shows that weathered diesel will ride over ice rather than under it, and there is no danger of diesel sinking in the much more dense sea water.

Work Sheet #3: Oil Spill Budget

Work Sheet 3 provides a format to keep track of how much oil remains in place during the spill response effort. This scenario provides an example of how this can be done. The distribution of the spilled oil on the pad and in the water is not intended to be predictive of how a diesel spill might occur on a gravel island. The distribution of the spilled diesel was just developed to show how to keep track of the oil that was spilled.

The sample work sheet for day 1 shows how the oil could have been distributed at the end of the first day. Some of the gravel is coated with oil, but even though this covers a fairly large area, it only represents about 1% of the oil spilled on the island. Most of the oil on the island is in the 5 and 10 mm pools.

The oil on the water quickly spreads to a very thin layer that is surrounded by a sheen. Here the thicker layer is estimated to be 0.02 mm and the sheen is estimated to be 0.005 mm. (The evaporation curve for 0.1 mm was used for the thicker part of the slick as an approximation.) It probably would not be possible to measure such thin slicks in an actual diesel spill. This is why a slick thickness of 0.1 mm was used as an approximation. The sheen that surrounds this layer may not be visible at all.

Making fine measurements to get an accurate spill budget will be very difficult in the field, but don't be discouraged. It's important that you use the best information that is available to establish the initial conditions and continue calculations from there. If the spill volume is known quite accurately, try to measure the slick thickness as close as possible and use that to compute the area covered by the spill. On the other hand, if the spill volume is not known, it may be necessary to go out to measure or estimate the area and combine this result with slick thickness to obtain spill volume. In any case, use the best information that is available, make an initial estimate of the spill volume and size, then stick to it. You may never know exactly how much oil was spilled, but it is important to keep track of the relative amount of oil that has been removed after the spill either by evaporation or the spill response effort.

The numbers shown on the sample Work Sheet 3 are rounded off considerably, but this must be expected in preparing a spill budget. It is important to establish a baseline using the best information that is available and then make consistent adjustments to that baseline in the days that follow. Note that in the spill budget for the first day the total is not 20,000 gallons. This is because evaporation has occurred during the first day. If areas covered by the spill are measured on the following days, the total volume of the spill should be less because of evaporation. If the areas cannot be measured on all of the days following the spill, it is still possible to estimate the volume of oil in the environment using the evaporation curves. To do this, you must apply the appropriate percent remaining to the initial spill volume, not the amount that remains at the end of the first day (or at the time that the volume estimate was made). In this scenario there was 72% of the .1 mm slick remaining at the end of the first day and 66% remaining at the end of the third day. Therefore, you must divide the volume remaining at the end of the first day by 0.72 and then multiply by 0.66 to estimate the amount that would be remaining at the end of the third day. This is what was done on the work sheet for days 3 and 10.

The new estimates of spill volume for days 3 and 10 were based entirely on the evaporation rate recorded on Work Sheet 2. At the end of the tenth day the total amount of the spill in all locations is a little more than 15,000 gallons. This is about 77% of the amount that was spilled on day one, so about 23% was lost to evaporation in ten days.

Work Sheet #4: Spill Volume Remaining

Work Sheet 4 shows a summary plot of oil remaining from day 1 to day 10 of the spill. Two plots are used because of the large difference in volume of oil on the water and oil on the gravel island. In practice recognizing this difference is practical because the cleanup problem for the oil on the island is entirely different from the recovery of oil from the water. Work Sheet 4 shows oil remaining on the gravel island. Because the 0.1 mm coating on the gravel is such a small volume of oil, it is not shown by a separate line but it is included in the total. Work Sheet 4 shows the volume of oil remaining on the water. In this case the sheen that surrounds the thicker part of the slick is not shown with a separate line but it is also included in the total.

These two plots on Work Sheet 4 show the spill losses due to evaporation. In a real spill response situation it would also be convenient to plot the reduction of spill volume resulting from recovery. These volumes could be measured fairly accurately and plotted on Work Sheet 4. This would provide the OSC with a good summary of exactly how the response effort was going.

Work Sheet #5: Evaporation Rate

Work Sheet 5 shows a plot of percent of the oil remaining based on the evaporation curves. The numbers plotted are taken from Work Sheet 2.

Work Sheet #6: Spreading on Open Water

Work Sheet 6 provides space to record all of the information needed to estimate spreading and drift on open water. Sources of information for each item number are recorded below.

1) Observe and measure spill radius if possible; however, if this cannot be done, estimate spill radius

for arctic diesel using Figure 3.1.3. The 20,000 gallon spill is expected to reach terminal thickness in 23 hours, therefore values for days 3 and 10 are not recorded. The thick part of the slick is expected to be about 0.1 mm thick, or even less, maybe 0.02 mm. Since it would not be possible to make this fine a measurement in the field, 0.1 mm is used as a likely upper limit. The thick slick would be surrounded by a sheen about 5 microns (0.005 mm) thick.

Figure 3.1.5 is provided as a fall back position to estimate spill size or slick thickness. Figure 3.1.5 simply takes spill volume and thickness and computes a radius of the area covered by a spill if it were circular and continuous. The radius is used because it is very difficult to measure, or even estimate, spill area in the field. Radius can be measured, or estimated, from a surface ship in the spill area or by flying over the slick. In any case, Figure 3.1.5 can be used in a number of ways. If spill volume is known and slick thickness can be measured, then the spill radius can be estimated from the curves. On the other hand, if spill radius can be measured or estimated and slick thickness can be measured, then spill volume can be estimated.

2) Slick thickness should be measured if possible. In this case it is estimated to be 0.1 mm, but it could be even thinner than that, maybe even 0.02 mm.

3) The spill drift vector is plotted on Work Sheet 7. This process is described in the next section.

4) The minimum distance to the shoreline is the closest point of land from the spill site. This could also be where the spill response base camp is located. The maximum distance to the shoreline is the farthest point away from the spill site that the oil is likely to come ashore based on the estimated range of drift vectors. The time to reach the shoreline is the distance (both maximum and minimum) divided by the spill drift velocity in that direction.

5) The estimated time to reach the shoreline is the time computed in item 4 added to the time of the spill event.

6) The length of the shoreline contaminated should be measured. It could be estimated based on the range of the drift vectors, but this would only be good for planning the spill response effort. Once the length of shoreline coated is known, the Retention Index can be determined from the charts in Section 4.

7) The distance to the pack ice has to be measured. The number used here is just typical for the time of year. The time to reach the pack is distance to the pack divided by the drift velocity in that direction.

8) The estimated time of arrival at the pack ice is the time computed in item 7 added to the time of the spill event.

9) The length of pack ice contaminated should be measured. The number shown here is what might happen considering the range of spill drift vectors.

10) The estimated drift of pack ice is taken from Table 5.4.1.

Work Sheet #7: Plot of Spill Drift

Determine the spill drift vector from a maneuvering board plot on Work Sheet 7. The spill drift calculation on Work Sheet 7 shows the current vector, 300°T at 0.3 kts drawn from the origin. The average current is taken from the area chart in reference (1). The prevailing northeast wind (blowing from 045°T) has an

average velocity of 10 knots (reference 1). Three percent of this velocity effectively drives spill at 0.3 kts. The wind vector is connected to the end of the current vector and the resultant principal direction of spill movement is 270°T at 0.5 kts. (This resultant is shown at point 1.) Although the prevailing wind is from 045°T, there is also a relative high frequency of winds coming from the east and north-north east. To show this distribution of predominant winds, vectors from these direction are also connected to the end of the current vector to obtain the range of directions and velocities of the spill drift due to current and wind. For this scenario, the range of directions and velocities is from 262°T at 0.45 knots to 285°T at 0.55 knots. (The vectors for this range are shown at point 2.)

The spill drift vector calculated on Work Sheet 7 is now plotted on Figure 5.4.3. Figure 5.4.3 is a page from reference (1), which is expected to be used along with this section of the field guide. Work Sheet 6 together with Figure 5.4.3 provides the basis for the solution to the spill drift problem.

From Figure 3.1.3, the thick part of the spill would be a circle with a radius of about 1,130 m, bounded by a sheen that extends out an additional 290 m. Figure 3.1.3, however, assumes spreading with no current or wind. In practice, the spill will not drift in the shape of a circle. When the spill surface remains continuous, it could be expected to be in more of a tear drop shape than a circle. There is also a good possibility that the spill will be broken up into patches and windrows rather than remaining continuous. The shape shown on Figure 5.4.3 is a circle in the direction of movement with an elliptical tail. This shape has the same area as a circle with a radius of 1,130 m.

The principal drift vector of 270°T and 0.5 kts would carry the spill to Cottle Island, a distance of 11.3 nm, in a little more than 22 hours. If the wind gives the drift a more northerly component, the spill would reach Bodfish Island in 28 hours or could even be carried farther to the north to other barrier islands or the pack ice. Table 5.4.1 shows the average monthly pack ice drift converted from reference (1) to nautical miles per day.

The important point to note is that the spill seems to be headed for the lagoon entrance between Cottle Island and Long Island. Reference (1) notes that water enters the lagoon driven by easterly winds, which prevail in this area. The large opening between Long Island and Cottle Island (0.4 nm) permits a large flowthrough of nearshore waters. The tide may increase or decrease the flow through the opening, but inside the lagoon, the tide and current generally act together to produce an east to west flow.

So here we have the spill heading for an opening in the barrier islands where there is a natural flow into the lagoon. Once through the lagoon entrance, the spill is then free to spread again, but now on the more sensitive mainland shoreline. This phase of spreading and potential for shoreline impact is shown in Figure 5.4.4 and described in item 6 of Work Sheet 6.

Figure 5.4.4 is reprinted from the shoreline impact charts in Section 4 of this Field Guide. The length of shoreline contaminated is shown as indefinite because if there is an northeasterly component to the wind drift, the spill could coat the shoreline beginning at Beechy Point and continue into Simpson Lagoon.

The principal shoreline type is a lagoon-facing mainland shore. There would be at least a moderate amount of impact here because low wave energy would result in slow removal and some of the spill could be redistributed from time to time to contaminate down-stream beaches. The spill may also persist for years because of the low transportation rates. There is an extensive marsh area just south of Beechy Point and more west of Beechy Point. Although the marsh represents only a small percentage of the coast line, these areas are highly sensitive and spill impact could be enduring. Oil that entered the marshes would be nearly permanent.

One possible solution to the problem would be to boom off the lagoon entrance between Cottle Island and Long Island. This is the natural place for the oil to collect, and it should be prevented from entering the lagoon where the spill impact is likely to be much more severe than on the barrier islands. There is also some chance that the oil could go through the lagoon entrance between Bodfish Island and Cottle Island, but using prevailing wind conditions, this is less likely. This is a secondary danger area.

If the oil does get inside the lagoon, it is likely to remain there for a long time and could do extensive damage. The first line of defense therefore is to protect the lagoon.

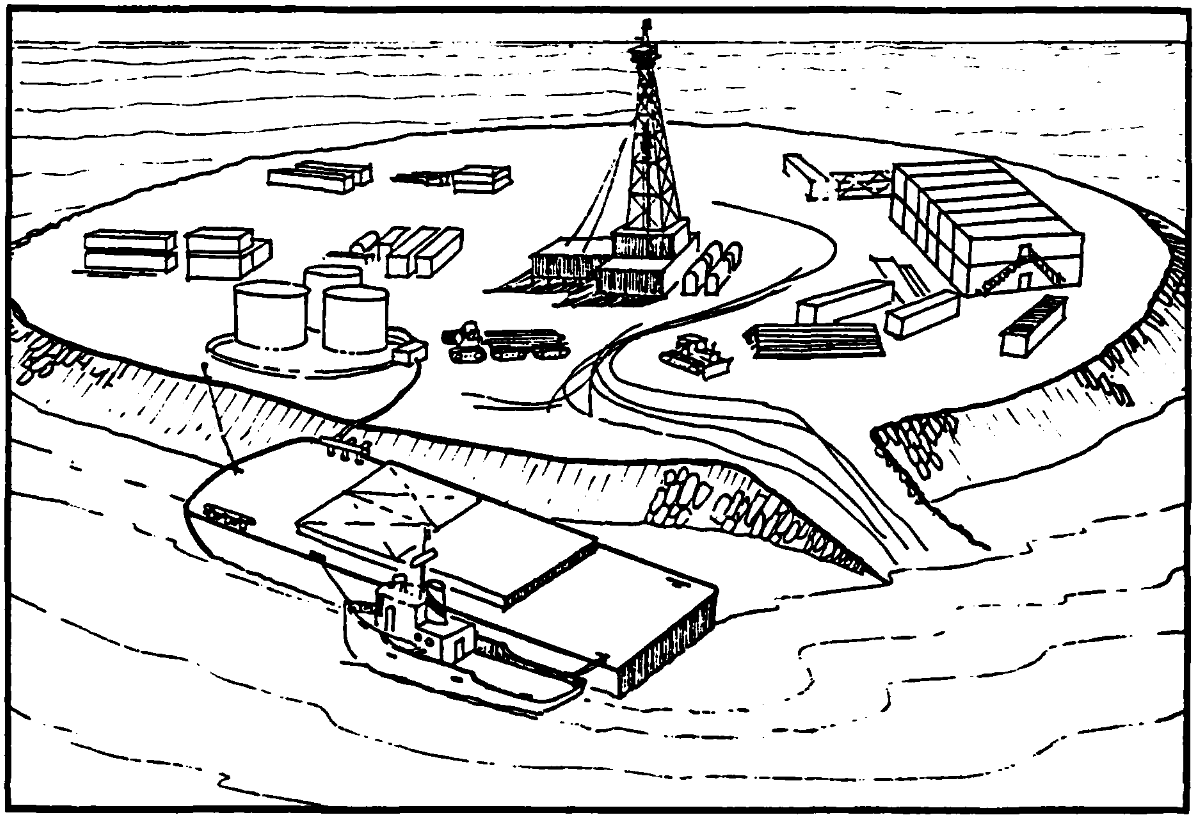


FIGURE 5.4.1 TRANSFER OF ARCTIC DIESEL TO A GRAVEL ISLAND

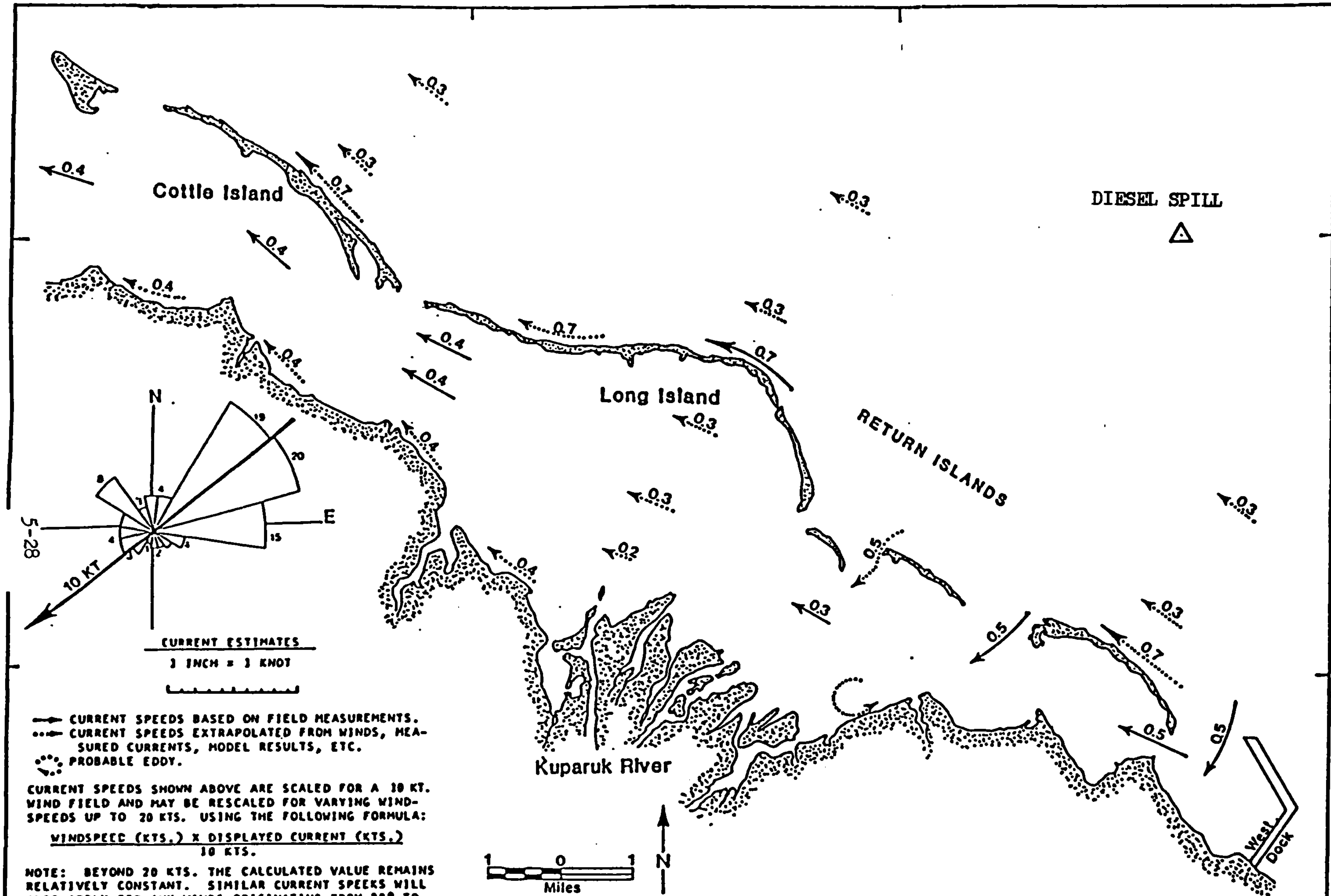


FIGURE 5.4.2 ARCTIC DIESEL SPILL LOCATION

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 1

DATE AND TIME SPILL BEGAN 1400 Local 1 August

SPILL LOCATION 70-30N, 48-35W TYPE OIL Arctic diesel

AMOUNT SPILLED 20,000 gallons

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) 4°C 2) SP. GRAVITY (g/cc) 0.804

3) VISCOSITY (cp) 0.42 4) POUR POINT (°C) -51°C 5) SOLUBILITY $5\ g/m^3$

6) SLICK THICKNESS (1) 0.005 mm (3) 5 mm
(2) 0.1 mm (4) 10 mm

7) COMBUSTIBILITY Oil pooled on gravel island highly combustible, but no combustibility for oil spread on water.

8) EMULSIFICATION None

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) Average 055°T/10 kts; Range, E/10 kts. to NE/5 kts.

10) TEMPERATURE (°C): AIR 4°C (39°F) 11) WATER 0°C 12) ICE none

13) WATER DEPTH (m) 11 m 14) WAVE HEIGHT (m) 90% 1.5m 15) CURRENTS 300°T/0.3 kts.

16) TIDE (m) 0.05 to 0.1 17) STORM SURGE HEIGHT ABOVE MSL (m) 2

18) ICE CONDITIONS Open water, some chunks of ice melting in area

19) PRECIPITATION Winds from all directions may carry rain 5 to 10% of the time and snow 2 to 5% of the time.

20) VISIBILITY Fog 25% of time for all wind directions 21) DAYLIGHT (HRS) 23

SPILL BEHAVIOR WORK SHEET #2

PHYSICAL PROPERTIES AFTER WEATHERING

1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)	52	72	94	96	48	66	88	92	40	58	83	86
4) VISCOSITY (cps)			1.2				1.3				1.4	
5) POUR POINT (oC)			-46				-42				-37	
6) DENSITY (g/cc)			.83				.84				.85	
7) SOLUBILITY (g/m3)			1.4				.7				.35	

REMARKS: Slick 1) 0.005 mm, 2) 0.1 mm, 3) 5 mm, 4) 10 mm

SPILL BEHAVIOR WORK SHEET #3
OIL SPILL BUDGET
SCENARIO 1

Day 1

Location	Thickness	Area	%Remaining	Volume
GRAVEL ISLAND	0.1 mm	100 m^2	72	0.01 m^3 (3 gal)
GRAVEL ISLAND	5 mm	80 m^2	94	0.4 m^3 (106 gal)
GRAVEL ISLAND	10 mm	50 m^2	96	0.5 m^3 (132 gal)
			Total	240 gal
BEAUFORT SEA	0.02 mm	4,000,000 m^2	72	70 m^3 (18,500 gal)
BEAUFORT SEA	0.005 mm	240,000 m^2	52	1.1 m^3 (300 gal)
			Total	19,040 gal

Day 3

Location	Thickness	Area	%Remaining	Volume
GRAVEL ISLAND	0.1 mm	90 m^2	66	0.009 m^3 (2.8 gal)
GRAVEL ISLAND	5 mm	74 m^2	88	0.37 m^3 (99 gal)
GRAVEL ISLAND	10 mm	48 m^2	92	0.48 m^3 (127 gal)
			Total	229 gal
BEAUFORT SEA	0.02 mm	3,200,000 m^2	66	64 m^3 (16,960 gal)
BEAUFORT SEA	0.005mm	200,000 m^2	48	1.0 m^3 (277 gal)
			Total	17,466 gal

Day 10

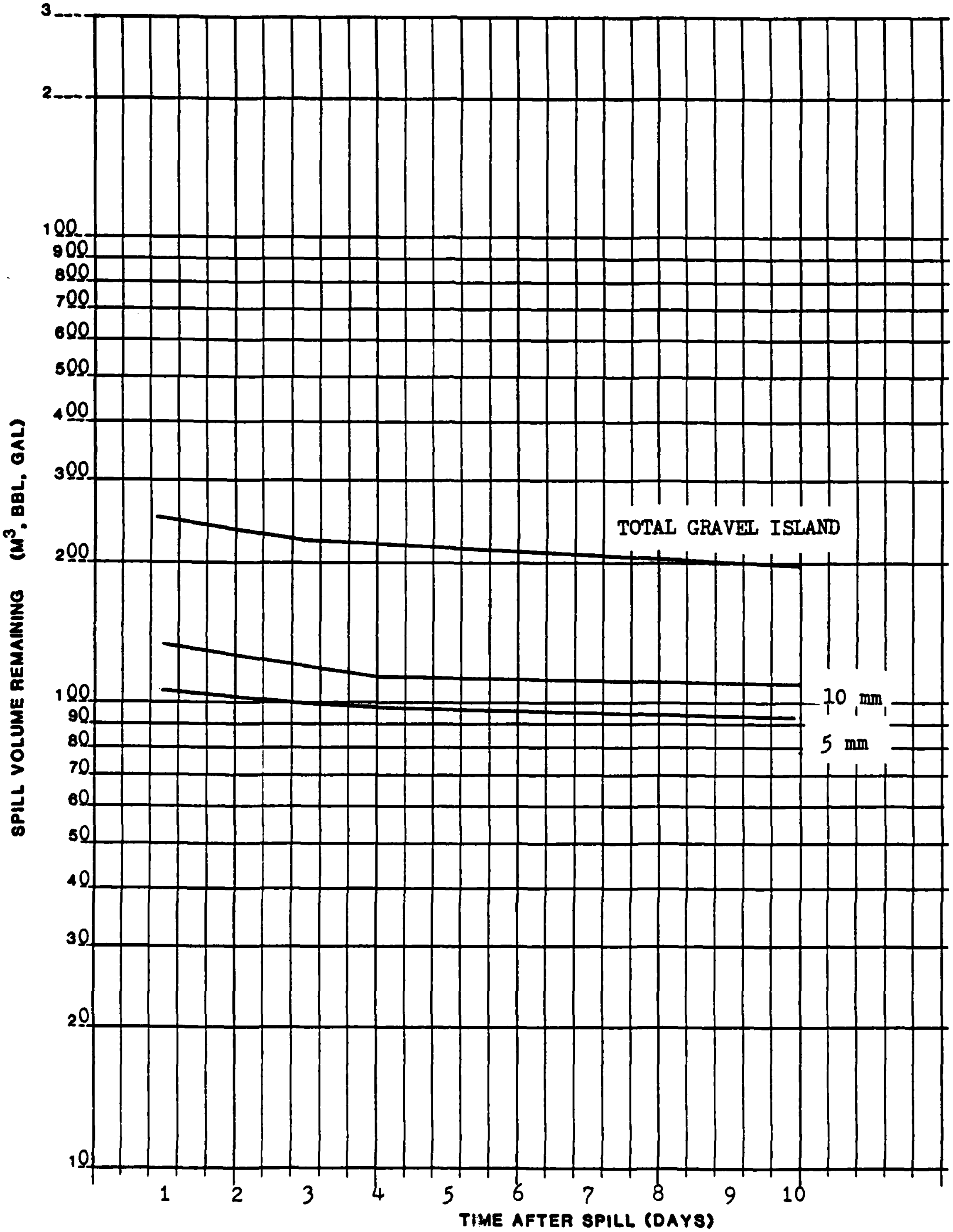
Location	Thickness	Area	%Remaining	Volume
GRAVEL ISLAND	0.1 mm	80 m^2	58	0.008 m^3 (2.4 gal)
GRAVEL ISLAND	5 mm	70 m^2	83	0.35 m^3 (94 gal)
GRAVEL ISLAND	10 mm	45 m^2	86	0.45 m^3 (118 gal)
			Total	214 gal
BEAUFORT SEA	0.02 mm	2,800,000 m^3	58	56 m^3 (14,900 gal)
BEAUFORT SEA	0.005 mm	170,000 m^3	40	0.85 m^3 (230 gal)
			Total	15,344

CONVERSION FACTORS:

1 BBL = 0.159 m^3 = 42 GAL
1 m^3 = 6.29 BBL = 264.2 GAL

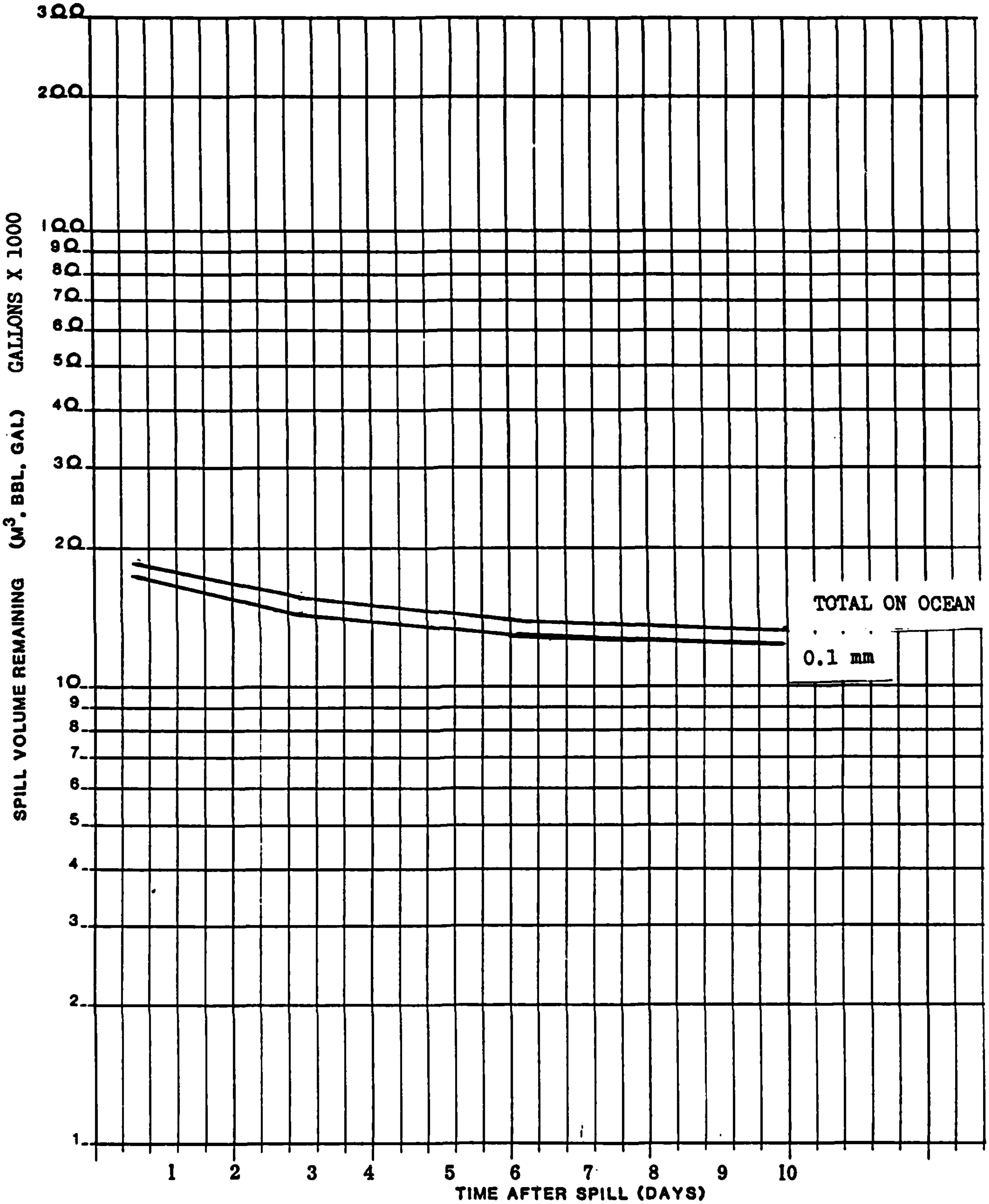
SPILL BEHAVIOR WORK SHEET #4

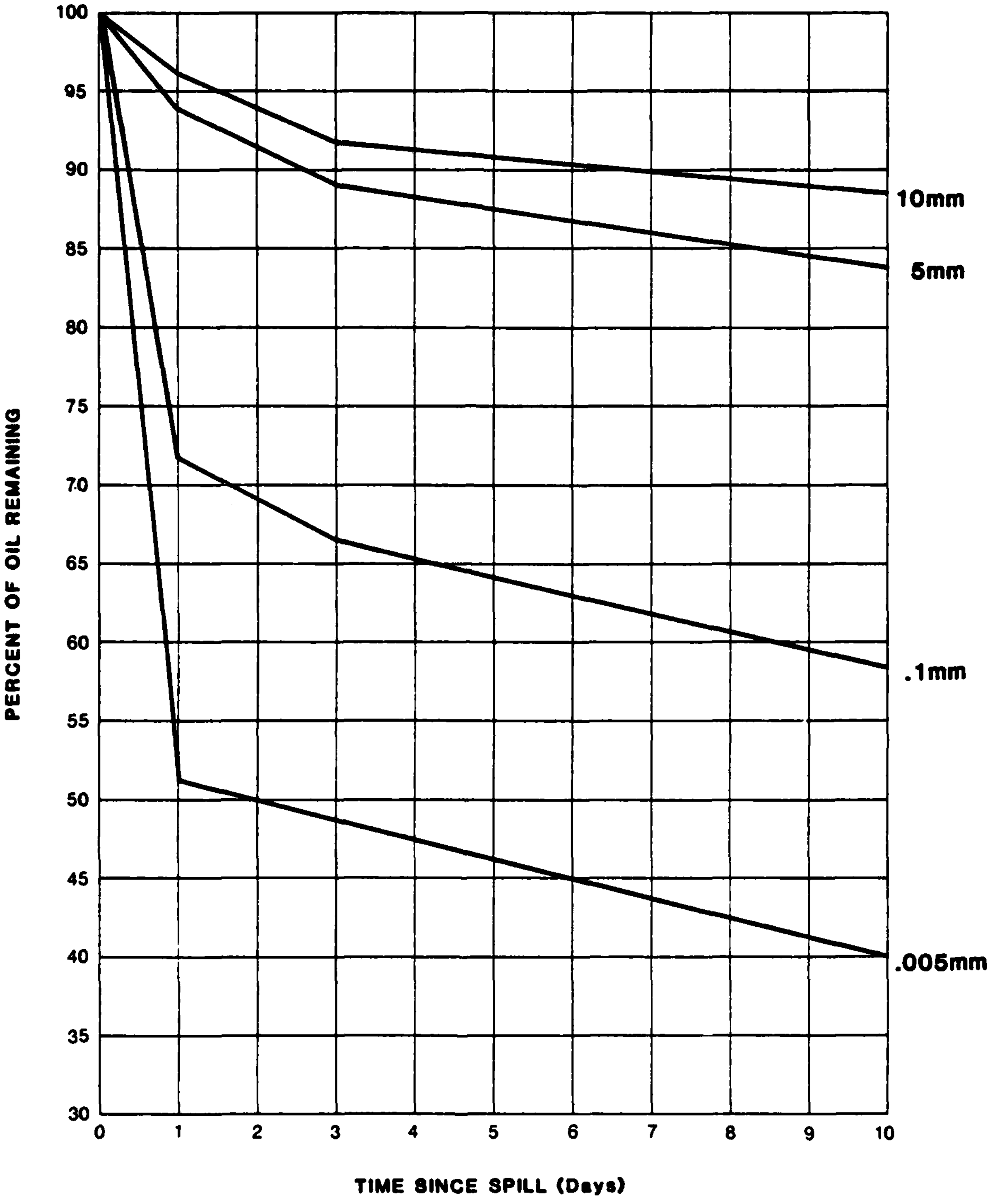
SPILL VOLUME REMAINING



SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING





SPILL BEHAVIOR WORK SHEET # 5

EVAPORATION RATE

SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER
SCENARIO 1

		THICK SLICK	THIN SLICK
1)	SPILL RADIUS (m):	1,130	290
2)	SICK THICKNESS (mm):	0.1	0.005

3) SPILL DRIFT VECTOR: AVERAGE 270°/0.5 kts RANGE 262°T/0.45 kts 285°T/0.45 kts

4) DISTANCE TO SHORELINE (NM): MAX 15.6 MIN 9.4

TIME TO REACH SHORELINE (HRS): MAX 28 MIN 20

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST 1000 2AUG LATEST 1600 2AUG

6) LENGTH OF SHORELINE CONTAMINATED (NM): INDEFINITE

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	INDEFINITE
2		6	
3		7	
4		8	0.6

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- o SHORELINE TYPE 5) Lagoon - facing mainland shore: 8) Marsh
- o IMPACT 5) Slow removal because of low wave energy; oil could be released later on other beaches: 8) Could seriously alter biological balance; could have significant affect on chain of nutrient interactions.
- o PERSISTENCE 5) Could persist for years because of low transport rate: 8) Virtually permanent after evaporation loss.
- o PROTECTION 5) & 8) Boom off lagoon entrance
- o CLEAN-UP 5) Recover oil collected in boom; clean beach to protect tundra margin: 8) Clean up likely to be counter productive.

7) DISTANCE TO PACK ICE (NM): 20 TIME TO REACH PACK ICE(HRS) MAX 56 MIN 40

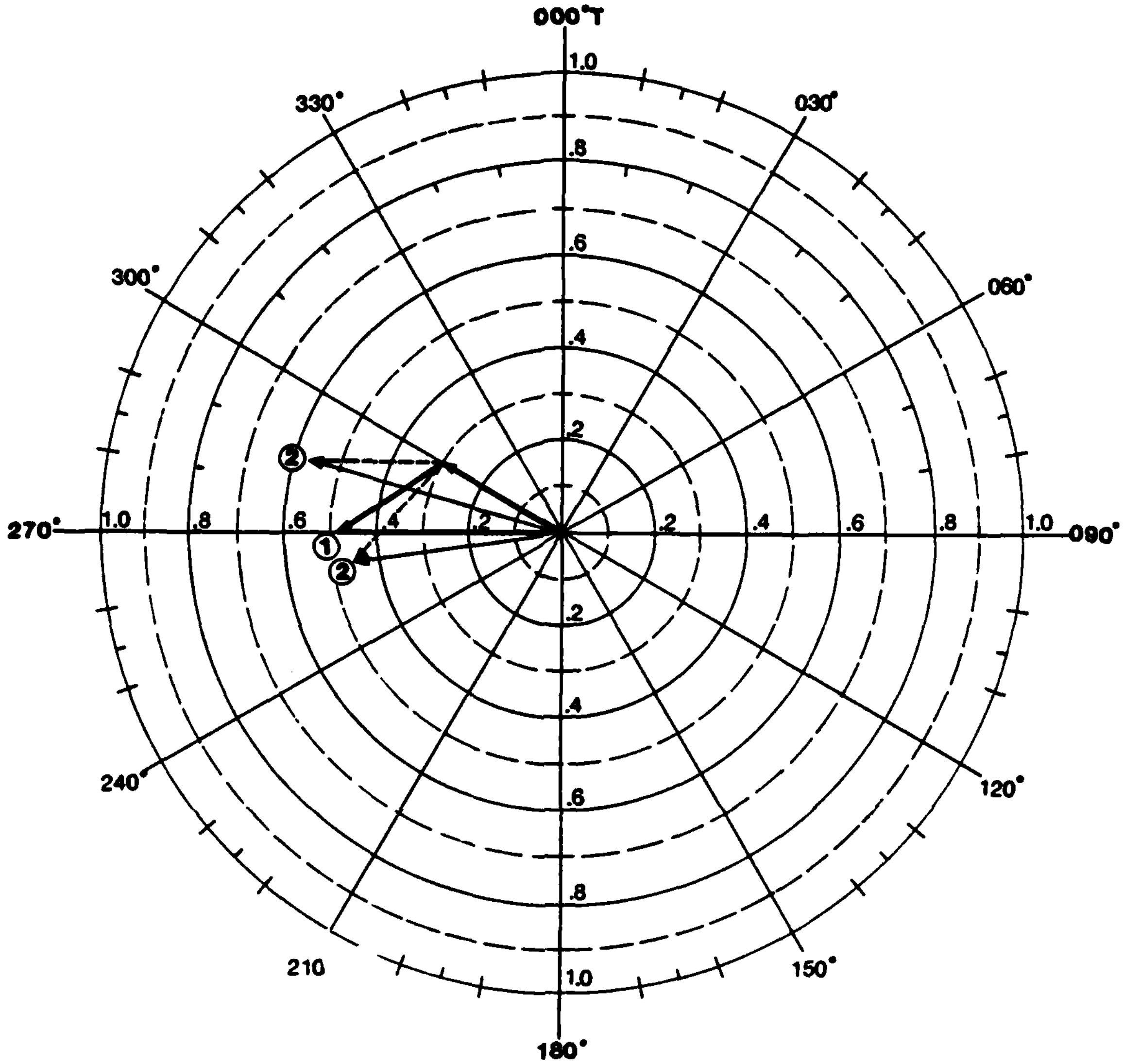
8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST 1600 2 Aug LATEST 0800 3 Aug

9) LENGTH OF PACK ICE CONTAMINATED (NM) 5

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) WEST 6.1 NM/DAY

SPILL BEHAVIOR WORK SHEET #7

PLOT OF SPILL DRIFT



SCENARIO I

1. Principal spill drift vector 270°T/0.5 kts

2. Range of spill drift vectors 262°T/0.45 kts to 285°T/0.55 kts

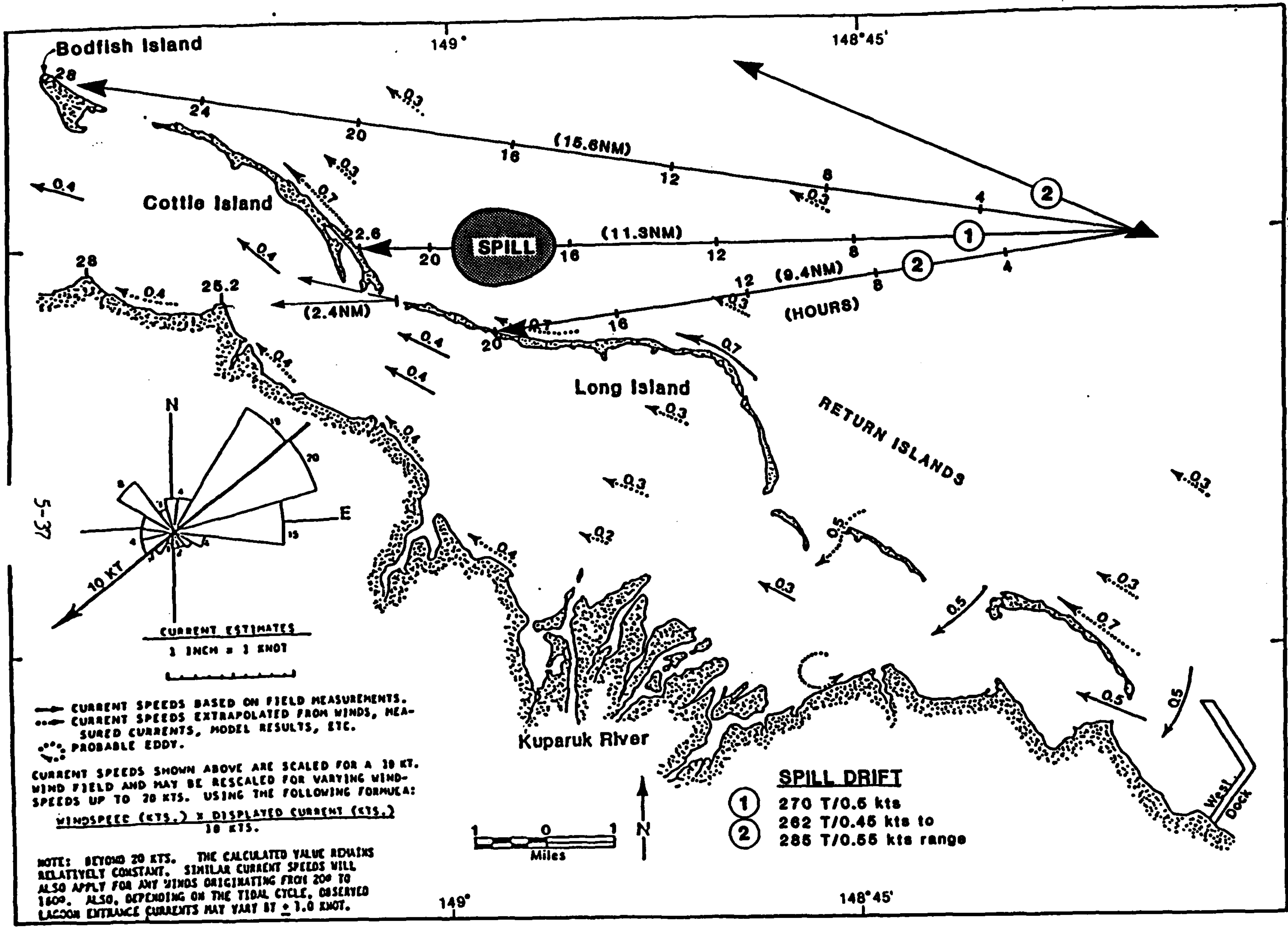


FIGURE 5.4.3 PLOT OF SPILL DRIFT, DIESEL SPILL

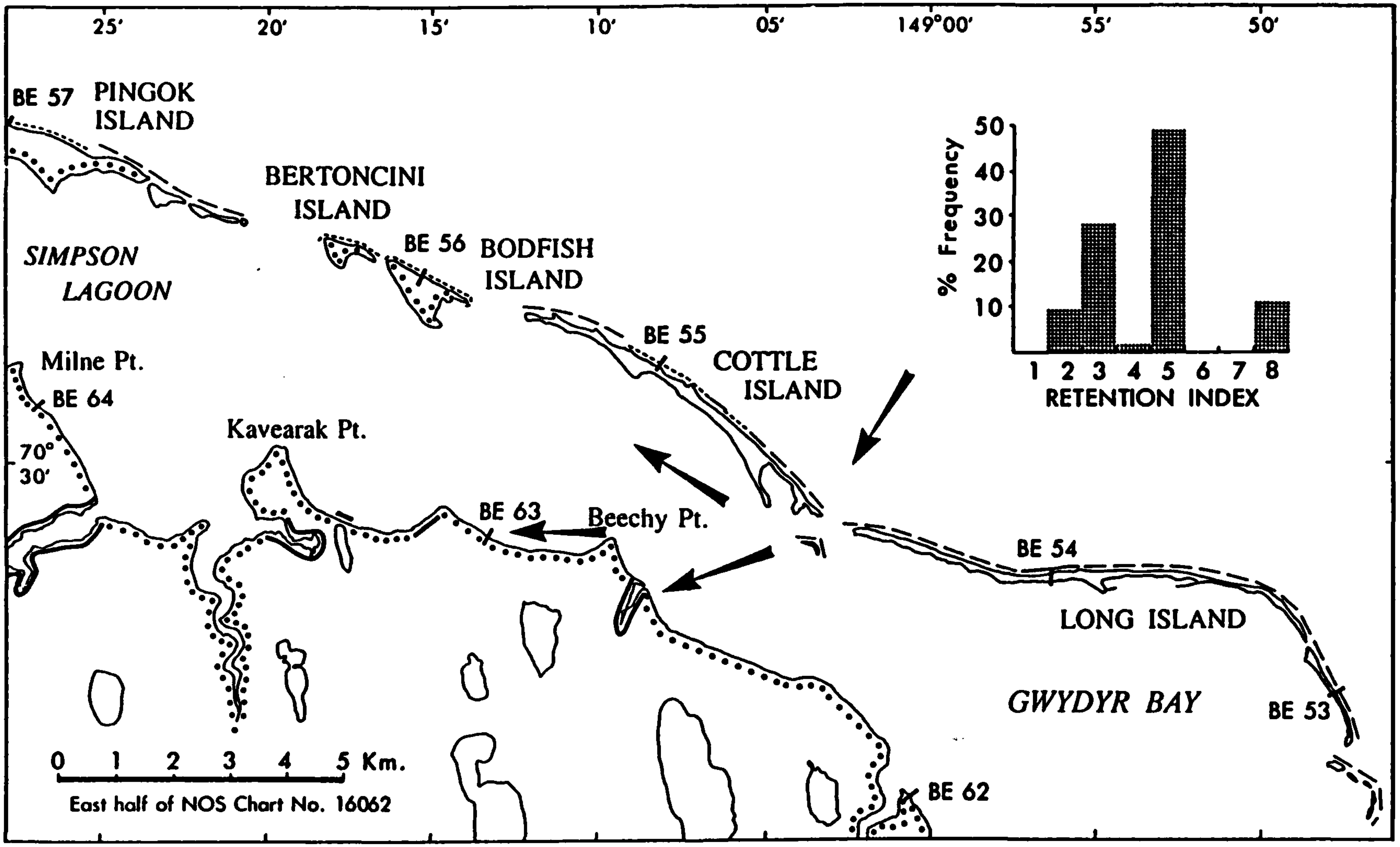


FIGURE 5.4.4 SPILL IMPACT IN SIMPSON LAGOON

5.4.2 SCENARIO 2 - FREEZE-UP

North Slope crude begins to leak from an undersea pipeline at about 1600 local time on 15 October.

Spill Location: The spill occurs at 70-45N, 151-43W, about 12 miles east of Cape Halkett. Figure 5.4.5 shows the location of the spill.

Season: Freeze-up, during the middle of October.

Spill Description: At about 1600 local time a feeder pipeline from an offshore oil well begins to leak at a rate of about 500 barrels of oil per day. Because the rate of release is relatively low, the leak is not detected with a pressure drop in the line.

There is only a little more than 6 hours of daylight in October (see Figure 5.3.1) so when the spill begins at 1600 it is already quite dark and the spill is not detected. Although an aircraft flies the route of the pipeline every day to detect leaks, the relatively small amount of oil that is released is still not detected on the second day either. At noon on the third day of the spill the crew of the surveillance aircraft sights the discolored ice and confirms on a low pass that the dark spot does in fact mark a spill. The spill is reported and at 1400 on 17 October the pipeline is secured. The oil that is already in the pipeline continues to leak for another two hours. At 1600 local a surveillance flight confirms that the flow of oil seems to be stopped. The pipeline supervisor estimates that 500 bbl of oil per day was released for a period of two days, so that a total of 1,000 bbl of crude oil is in the water and mixed with the ice.

Development of Work Sheet Entries

Work Sheet #1: Initial Conditions

This section tells where you can find the necessary information and how to make calculations and estimates.

For initial conditions, items 1) through 5) record the known physical properties of the oil. Although the well head temperature is about 60°C, the oil escaping from the pipeline will be quickly chilled to the water temperature, which is close to -2°C. The other items for initial physical conditions can be obtained from oil company records.

Measure the slick thickness in as many areas as possible. If you can't measure the thickness, estimate it by entering Figure 3.1.5 with spill volume and radius. There will probably be a range of slick thicknesses. Two possible thicknesses are used for this scenario.

The assessment of combustibility, item 7, is taken from the description in Section 2.7.4 of the text. Item 8, the estimate of emulsification, comes from Section 2.8.

The Environmental Conditions, items 9 through 17, are the average conditions for October for the spill area. These values were obtained from reference (1).

Ice conditions, item 18, should be observed at the spill site. The ice conditions described for this spill scenario are the average conditions for October for the spill area shown in reference (1). Some of the additional details describing these conditions were obtained from Section 1.0 of this text.

Items 19, precipitation, and 20, visibility, are average conditions

for the area obtained from reference (1). The hours of daylight, item 21, were taken from Figure 5.3.1.

Work Sheet #2: Physical Properties After Weathering

The physical properties are recorded for days 1, 3, and 10 because these times provide points that best describe the weathering envelope. For this scenario, slicks 1 and 2 correspond to slick thicknesses of 5 mm, and 10 mm as shown in item 6 of Work Sheet 1. The evaporation history of each slick is determined from Figures 2.1.2 and 2.1.3 and is recorded in item 3 of Work Sheet 2. Evaporation represents the most significant loss of spilled oil to the environment. To get a better idea of how the evaporation occurs, plot these points for days 1, 3, and 10 on the blank graph provided on Work Sheet 5. Since only three points are plotted for each slick, the curves are not rounded out to show the full extent of the evaporation. For example, additional points plotted between day 3 and day 10 would round out the curve and show a slightly higher rate of evaporation than the straight line graph. Notice that the evaporation losses for crude oil are not as high as for arctic diesel. The oil mixed in grease ice and pooled between the pieces of pancake ice would probably not evaporate quite as fast as shown for the 10 mm slick. As an estimate, evaporation may be 2 to 5% less than for the curve shown.

The viscosity of the weathering crude, item 4, is significant. Figure 2.2.1 shows that as the oil is chilled and weathered by the wind on the first day, the viscosity moves quickly from the thick, syrup-like range to the semi-solid range. Figures 2.2.2 through 2.2.4 show that as the oil continues to weather over a 10 day period, it becomes much more viscous. Some of the oil that is under ice or mixed with ice will not weather quite as much because it is not completely exposed to the wind. However, the viscosity curves show that even for 5 knots of wind the oil is semi-solid. As the water and ice quickly reduce the temperature of the oil to 0°C or even a bit lower, it will become semi-solid even with no exposure to the wind.

The pour point in item 5 tends to confirm what has already been demonstrated by the increase in viscosity. This spilled crude quickly becomes very viscous and will not spread. Figure 2.3.1 shows that even though the pour point starts at -10°C, in only a few hours it goes to 0°C and by the end of the first day it is already +5°C. By the tenth day the pour point is +12°C (54°F). There will be very little movement of this oil in an environment where it is in a bath of water and ice at -2°C and chilled by air at -10°C.

Item 6, density, is also significant. The density of grease ice is about 0.99 g/cc and the density of pancake ice is about 0.93 g/cc (Section 3.3.3). Since the crude oil has a density of about 0.89 g/cc when it is first spilled, there will not be much movement of oil under ice. After the third day, the weathered crude may be slightly more dense than the pancake ice so there could be some movement under ice. As a practical matter, however, oil is most likely to stay in place, because the viscosity of the weathered oil is high by the third day and there is relatively little wind and wave energy.

There will be no measurable amount of spill lost because of solubility, (item 7), but dissolution of even small amounts of the crude could have an effect on water quality or benthic organisms.

<u>Work Sheet #3: Oil Spill Budget</u>

For this scenario, the oil spill budget must be based on the results of the spill spreading in broken ice, so go directly to review the results of Work Sheet 8, Spreading In Ice. These two sheets will be reviewed together.

Item 1 of Work Sheet 8 describes how the oil directly over the pipeline leak will be contained by the ice. The oil may herd the ice a bit and move between the pieces of ice to some extent, but in a short time it would be contained in the center by the field of ice around it.

This open water area above the leak does not have much capacity to contain oil, however. The freeboard of the grease ice/pancake ice is very low, so as soon as the open water area is full of oil, the oil would start spreading out over the grease ice and between the pieces of pancake ice. In addition, the oil that has drifted down stream from the leak will immediately move through the ice where it will also coat the pancakes and saturate the ice between the pancakes. This behavior pattern is recorded in item 2 of Work sheet 8.

The purpose of the oil spill budget is to determine the extent of spreading and the amount of oil that is in each ice environment. This was done be examining the way that oil moved in a field of pancake ice in a laboratory experiment and using these results to estimate the amount of containment that would be provided by the ice. The thicknesses of oil on the various ice features were measured on Figure 3.3.2 using the scale provided and these numbers were used to estimate the amount of oil that could be contained in the ice field, or put another way, the extent of spreading of oil in the ice field. The various measurements and assumptions are described in item 2 of Work Sheet 8.

The only general assumption made for these computations in item 2 of Work Sheet 8 was that the pancakes had a diameter of 30 cm. This is a typical size of ice feature in some fields of pancake ice, although the size of pieces is not generally regular and the field could be expected to include pieces much larger and pieces much smaller. For the purposes of making these calculations, there is not much advantage in trying to determine a distribution of ice piece size because the distribution is likely to be random and highly variable between locations. The important point is to use a typical ice piece size to estimate the extent of spreading.

Based on the randomness of the distribution of the ice field features and differences between ice fields, the reader may question the validity of the calculations and the estimates. This observation is justified, but the important point to remember is this: the purpose of performing these calculations is to determine if the spilled oil will spread out into a very wide area and drift away from the spill site, or whether it is more likely to be confined to a relatively small area.

The answer is that the spill is likely to be confined to a relatively small area. The spill budget estimated that it would be confined to the area of a circle with a radius of 106 m, which is a diameter of 212 m, or equivalent to the area of a square with a side of 188 m (0.1 nm). For an oil spill of 1,000 bbl, this is quite a small area indeed. Of course there could be a fairly wide range of inaccuracy in this estimate; however, the point can be convincingly argued that the <u>spill does not spread significantly, instead it remains confined to a relatively</u>

small area. This is the important news for the OSC.

Work sheet 3 shows the details of the oil spill budget. The spill budget can be developed by considering the ice field as a whole. Fly over the spill and measure or estimate the extent of the contaminated area. If possible, examine one section of the spill to determine how much oil is trapped on the pancakes, how much is pooled between the pancakes, and how much coats the underside of the ice. If this is not possible, estimate the amount of oil that is trapped around each pancake as described in item 2 of Work Sheet 8. Then measure or estimate the average size of the pancakes, and use this result to compute how much oil could be contained by a single pancake unit; that is, on the ice, between the ice, and under the ice. Then determine how many of these units are contained in the entire contaminated area. This will provide an estimate of the volume of oil that is contained in the contaminated area, and it does not require adding up the areas in and around the pancakes that are covered by oil.

Work Sheet 3, for day 1, shows this result for the pipeline leak scenario. These numbers have been reduced by the amount of evaporation for the first day except for the oil under ice, which is expected to have almost no evaporation. The volume in each area at the end of the first day shows that less than 1% of the spill is in the pool above the leak, about 58% is on the pancakes, 31% is between the pancakes, and 11% is under the pancakes. The data for days 3 and 10 show how the volume decreases with evaporation except for the oil under ice. These results are plotted on Work Sheet 4. (The amount of oil pooled above the leak is relatively small and is only included in the total.) These plots show that only a small amount of the oil is lost to evaporation.

Work Sheet #4: Spill Volume Remaining

Work Sheet 4 shows the record of spill volume remaining.

Work Sheet #5: Evaporation Rate

Work Sheet 5 shows the percent oil remaining after evaporation for a 5 mm and a 10 mm slick, which are typical of oil accumulations in the pipeline scenario.

Work Sheet #6: Spreading on Open Water

This Work Sheet is last because spreading on open water will not occur until break-up the following summer.

The oil in this scenario is frozen into place in a fairly small area in October. If a spill response effort cannot be launched effectively during the freeze-up period, the oil will remain in place until summer. Since the oil is pooled in the ice in a small area, there could be some opportunity for recovery by drilling down to oil lenses when the ice becomes thick enough to support men and equipment in the winter.

Whatever oil remains, however, will be released at break-up at the end of July or the beginning of August. The spill at that time will be thick, well below its pour point in water at about $0^{\circ}C$, and in clumps from about 30 cm across down to bits of millimeter size. The principal drift vector is $275^{\circ}T$ at 0.4 kts and the range is from $265^{\circ}T$ at 0.38 kts to $285^{\circ}T$ at 0.5 kts. (These drift vectors were computed on Work Sheet 7.) Figure 5.4.6 shows the area where the oil is most likely to contact on Cape Halkett. There are no protective barrier islands here so that the entire area is vulnerable to contamination. Oil could reach the

shoreline any time from 20 hours to 35 hours from the time that it is released. Of course other types of movement are also possible. For example, the oil could be carried with drifting ice before it is released, or the movement of the oil on water could be obstructed by floating ice. Movement with the ice for long distances is not too likely because the oil is near the surface and would be released to the water fairly early in the melting.

In any case, early in break-up the spill is likely to head west toward Cape Halkett. Figure 5.4.6 shows that the largest coastline type exposed is that typical of a lagoon-facing mainland shore (although a lagoon is not present in this case), peat shores, and the highly sensitive marshes. Just to the north of the expected beach impact point are several miles of sheltered tidal flats, another highly sensitive area. In all, the prospect is for the released oil to move fairly rapidly toward a long segment of sensitive, unprotected shoreline.

Protection of the Cape Halkett area would be difficult since there are no barrier islands. Protection of the shoreline would involve booming off the entire coast. The threatened area is 5 nm long, or perhaps even longer. In addition, the threat to the environment in this area is severe. The residence time of the oil on this shoreline is from years to nearly permanent. Currents and waves will provide natural removal of oil in some areas; however, the oil released from these shores may only be carried away by currents to contaminate other areas. The marshes, where the weathered crude would be expected to remain permanently, could become biologically dead.

Work Sheet #8: Spreading In Ice

Work Sheet 8 is described along with Work Sheet 3, Oil Spill Budget.

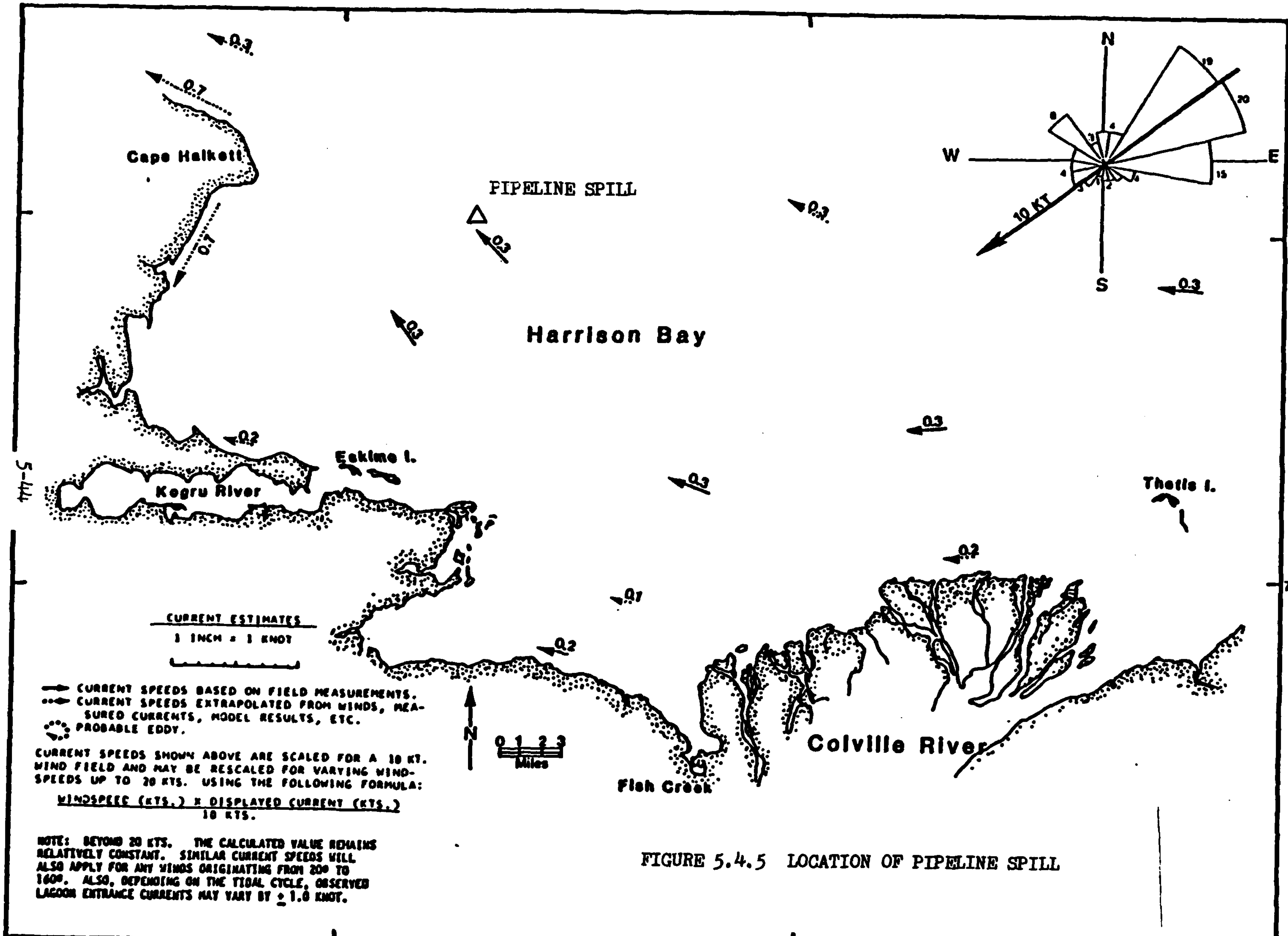


FIGURE 5.4.5 LOCATION OF PIPELINE SPILL

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 2

DATE AND TIME SPILL BEGAN 1600 15 OCTOBER

SPILL LOCATION E. OF CAPE HALKETT 70-45N 151-43W TYPE OIL PRUDHOE BAY CRUDE

AMOUNT SPILLED 1,000 BBL

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) -2°C (28°F) 2) SP. GRAVITY (g/cc) 0.895

3) VISCOSITY (cp) 35 4) POUR POINT (°C) -10°C 5) SOLUBILITY 29.2 g/cc

6) SLICK THICKNESS (1) 5 mm (3)
(2) 10 mm (4)

7) COMBUSTIBILITY Good for accumulations 5 mm thick, but accumulations may be too isolated to maintain combustion continuously. Recent tests indicate that oil can be burned in broken/brash ice environment, but it is likely that these burns would only be successful where there is a sufficient concentration of oil or where melting ice permits oil to collect in a central pool. (Section 2.7.4, p.2-17).

8) EMULSIFICATION Not likely.

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) 045° T/10 kts

10) TEMPERATURE (°C): AIR -10°C (14°F) 11) WATER -2°C 12) ICE -2°C

13) WATER DEPTH (m) 12 m 14) WAVE HEIGHT (m) Calm 15) CURRENTS 315°T/.3 kts

16) TIDE (m) .2 to .3 17) STORM SURGE HEIGHT ABOVE MSL (m) $\geq$ 2.5

18) ICE CONDITIONS 15 Oct 50 to 75% probability of 0.5 coverage. About 15 cm accumulated for mid-Oct. Wind and waves will cause pancakes to form that will later be frozen into a pattern that remains visible. Finger rafting, micro-ridges with a square tooth pattern would also form. Ice thickness would be doubled in rafting.

19) PRECIPITATION Snow showers 10% of the time

20) VISIBILITY Fog about 5% of the time 21) DAYLIGHT (HRS) 6.2
Vis <8 nm 50% of the time
Vis <1 nm 10% of the time

SPILL BEHAVIOR WORK SHEET #2

SCENARIO 2

PHYSICAL PROPERTIES AFTER WEATHERING

1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)	84	87			82	83			77	79		
4) VISCOSITY (cps)	2700	2200			4000	3200			6000	4900		
5) POUR POINT (oC)	+5				+8.2				+12			
6) DENSITY (g/cc)	.93				.94				.95			
7) SOLUBILITY (g/m3)	5				3.3				2			

REMARKS: Slick: (1) 5 mm, (2) 10 mm

SPILL BEHAVIOR WORK SHEET #3
OIL SPILL BUDGET
SCENARIO 2

Day 1

Location	Thickness (m)	Area (m^2)	%Remaining	Volume (m^3)(bbl)
POOL ABOVE LEAK	5 mm	78.5	84	0.33 (2)
OIL ON PANCAKES	4 mm	2.34×10^4	84	78.6 (494)
BETWEEN PANCAKES	12 mm	4.22×10^3	87	42.5 (267)
UNDER PANCAKES	1 mm	1.43×10^4	100	14.5 (91)
				TOTAL 854 bbl

Note: Areas do not add up to equal the total area covered because part of the surface of the pancake is not coated with oil, and the area of the underside of the ice coated by oil is not added to the total surface area contaminated.

Day 3

Location	Thickness	Area	%Remaining	Volume
POOL ABOVE LEAK	5 mm	---	82	0.32 (2)
OIL ON PANCAKES	4 mm	---	82	76.7 (482)
BETWEEN PANCAKES	12 mm	---	.83	40.5 (255)
UNDER PANCAKES	1 mm	---	100	14.5 (91)
				TOTAL 830 bbl

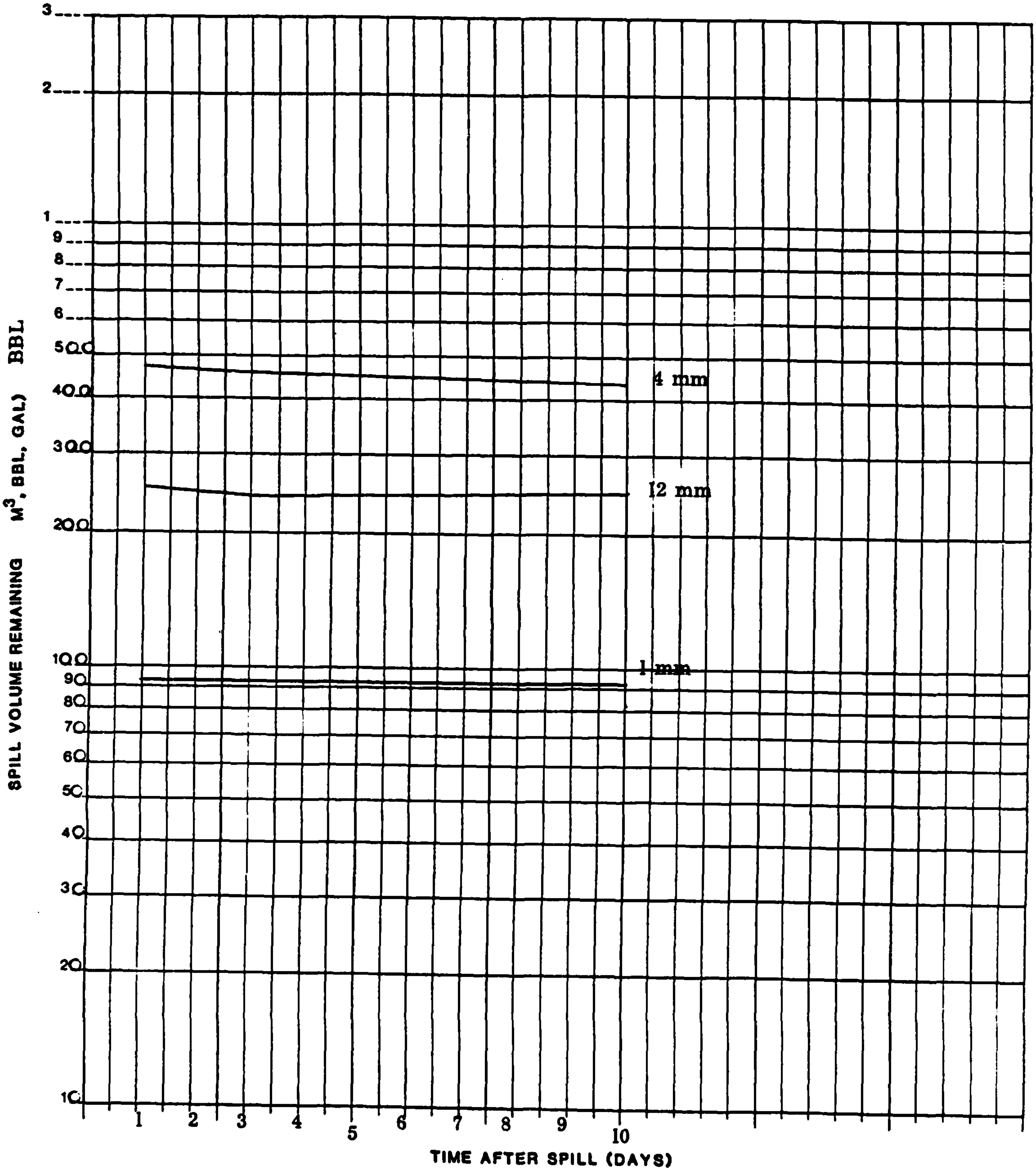
Note: As the oil weathers, the area covered is likely to remain about the same while the thickness decreases. For day 3 therefore, the volume decreases slightly for the nominal spill thickness shown.

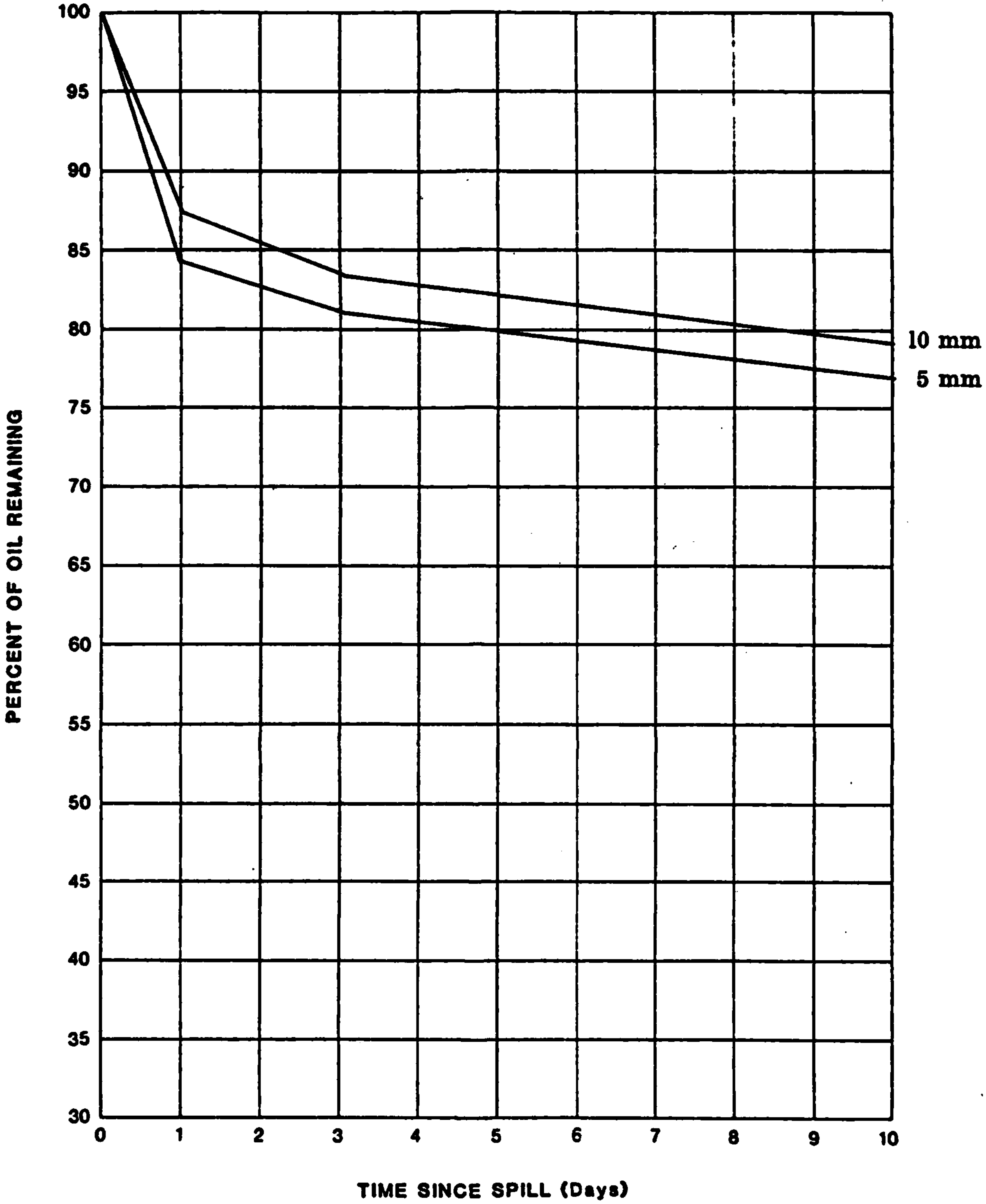
Day 10

Location	Thickness	Area	%Remaining	Volume
ABOVE LEAK	5 mm	---	77	0.30 (2)
ON PANCAKES	4 mm	---	77	72.1 (454)
BETWEEN PANCAKES	12 mm	---	79	40. (252)
UNDER PANCAKES	1 mm	---	100	14.5 (91)
				TOTAL 799 bbl

SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING





SPILL BEHAVIOR WORK SHEET #5

EVAPORATION RATE

SCENARIO 2

SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER
SCENARIO #2

		THICK SLICK	THIN SLICK
1)	SPILL RADIUS (m):	110	some sheen
2)	SLICK THICKNESS (mm):	4-12 mm	

3) SPILL DRIFT VECTOR: AVERAGE 275°T/0.4 kts RANGE 265°T/0.38 kts 285°T/0.5 kts

4) DISTANCE TO SHORELINE (NM): MAX 13 MIN 10

TIME TO REACH SHORELINE (HRS): MAX 35 MIN 20 (Estimate time from breakup)

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST ________ LATEST ________

6) LENGTH OF SHORELINE CONTAMINATED (NM): 4.8

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	3.4 nm
2		6	0.6
3		7	
4		8	0.8

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- o SHORELINE TYPE 5) Lagoon - facing mainland shore; 6) Peat shores: 8) Marsh
- o IMPACT 5) Low; 6) Could affect nutrient chain; 8) Could upset biological balance
- o PERSISTENCE 5) Years; 6) Many years; 8) Permanent
- o PROTECTION 5) Boom to protect shoreline; 6) Booms; 8) Booms
- o CLEAN-UP 5) Only narrow beaches to protect tundra; 6) recover and dispose of peat; 8) Not feasible

7) DISTANCE TO PACK ICE (NM): -- TIME TO REACH PACK ICE(HRS) MAX -- MIN --

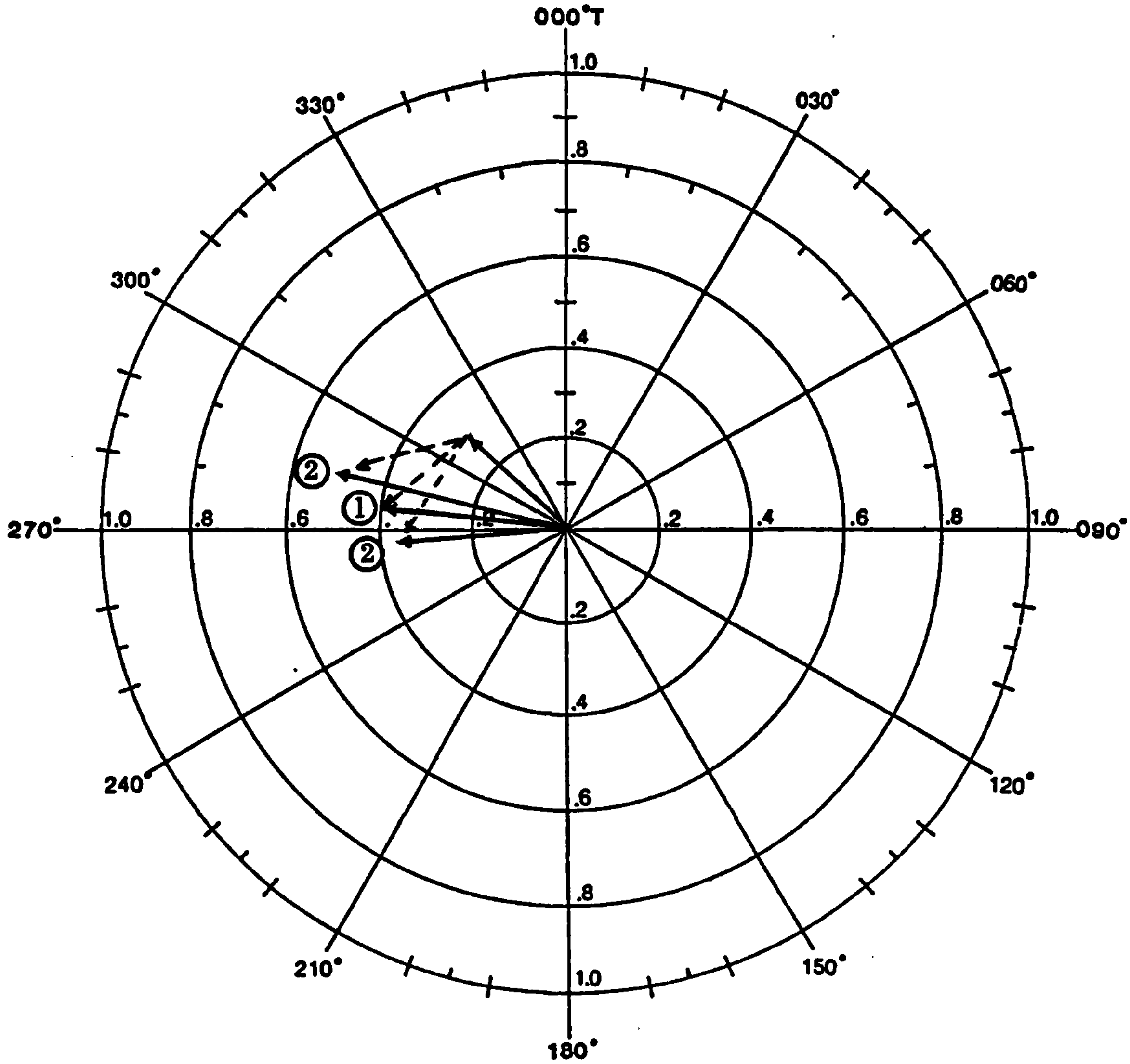
8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST -- LATEST --

9) LENGTH OF PACK ICE CONTAMINATED (NM) Low probability of encounter with pack ice.

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) ________

SPILL BEHAVIOR WORK SHEET #7

PLOT OF SPILL DRIFT



SCENARIO 2

1. Principal drift vector 275°T/0.4 kts

2. Secondary drift vectors 265°T/0.38 kts
   to 285°T/0.5 kts

SPILL BEHAVIOR WORK SHEET #8
SPREADING IN ICE
SCENARIO 2

SPREADING IN BROKEN ICE

1) SPREADING IN/AGAINST BROKEN ICE Some ice melting would occur over spill, but the relatively small amount of oil in cold water should chill quickly. Ice will provide some containment. Oil may herd ice if open water is available, but oil will move only a short distance into the the ice field. There could be some gravity spreading of oil over the ice if enough oil accumulates over the leak, but as it gets cold it is less likely to spread. Figure 5.3.1 shows a 1000 bbl spill with a radius of 40-70 m for thickness of 10-30 mm. At minimum thickness of 5 mm, the radius would be 100 m. This checks very well with an estimate made for spreading in pancake ice described below. North Slope crude would be completely contained by the ice after 1 day of weathering. If daytime temperatures were much warmer than normal, there could be additional spreading. If temperatures were colder than normal, spreading would be reduced.

2) SPREADING IN GREASE & PANCAKE ICE Crude will come right up through grease ice and float on the surface. Oil will occupy spaces between pancakes, plus, be pumped onto the surface of pancakes and held in place by the rim. (Fig. 3.3.2). Assume that the warm oil melts a pool with a radius of 5 m and a thickness of 5 mm right above the pipeline leak. Now use the spill configuration on pancake ice shown in Fig. 3.3.2 to compute the extent of spreading in that field. Fig. 3.-3.3.2 shows about 4 mm of oil being trapped on the pancake, a 12 mm thick 10 mm wide pool trapped between pancakes, and about 1 mm on the under side of the ice in an annulus about 40 mm wide. Assuming that the pancakes are 30 cm in diameter, 1,000 bbl of oil could be contained in an area with a radius of about 106 m. This means that this growing ice field has a large capacity to contain oil and the 1,000 bbl spill would be confined to a rather small area. Because the density of the grease ice is about 0.99 g/cc, and the density of the pancake is about 0.93 g/cc (Section 3.3.3), there will not be much movement of oil under ice since its density initially is 0.89 g/cc.

Oil on pancakes may also absorb some solar radiation causing the ice to melt so that the oil sinks in the ice and becomes frozen in when temperature drops. All of the oil is likely to become frozen in near the surface. Oil may become well mixed in brash ice. Figures 3.3.3 through 3.3.6 show photos of the kind of conditions that may occur.

3) SPREADING IN RAFTED ICE Under-ice relief is probably slight as ice is forming. Probably not much movement under ice because currents are low and oil is relatively viscous. Crude will probably be trapped by any under-ice features and then come to the surface as a result of seepage through the openings in these features. (Fig 3.7.4)

4) SPREADING IN RUBBLE & PRESSURE RIDGES These will be only slight features in new ice therefore they will not hold much oil. There could be some movement of oil up into small pressure ridges and rubble piles if the ice formation has voids and the oil has not become too viscous.

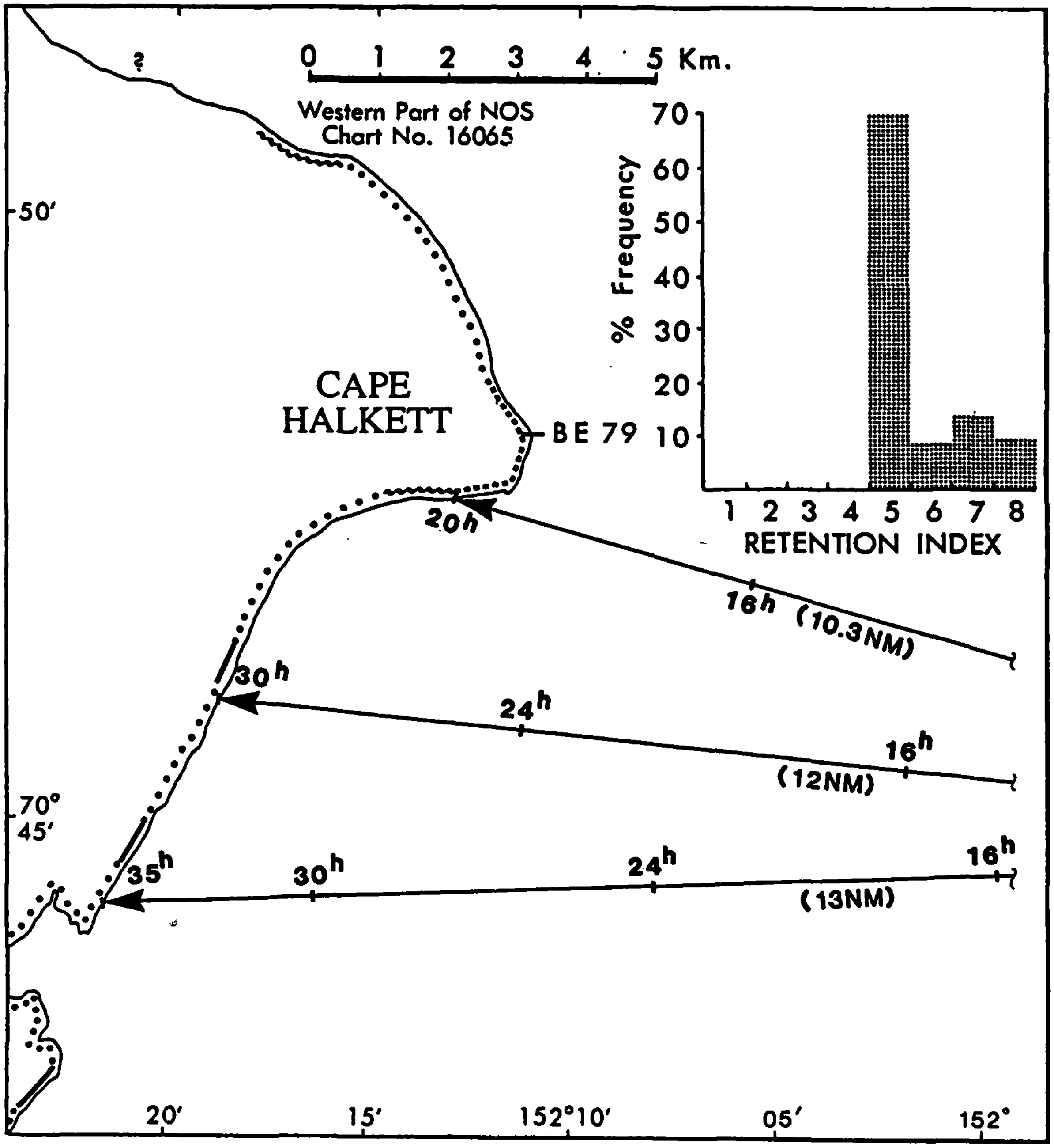


FIGURE 5.4.6 SPILL IMPACT ON CAPE HAI KETT
Numbers in parens show distance to
the spill site. (1 km=0.54 mm)

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5.4.3 SCENARIO 3 - WINTER BLOWOUT WITHOUT IGNITION

About noon on 15 March a well being drilled from a gravel island blows out of control.

Spill Location: The spill occurs on a gravel island at 70-30N, 148-35W, about 5 nm east-northeast of the north end of Long Island. Figure 5.4.7 shows the location of the spill.

Season: Fast ice, during the middle of March.

Spill Description: At about 1200 local time a well being drilled from a gravel island blows out of control. Initial efforts by the drilling crew to control the well are unsuccessful, and the resulting blowout is estimated at 10,000 barrels per day. The gas and evaporation of the lighter ends of the crude oil present an explosion and fire hazard in the immediate area of the blowout. The escaping gas may not be toxic to breathe, but it could cause suffocation to personnel not equipped with special breathing apparatus. Personnel, therefore are immediately evacuated from the gravel island using all available vehicles over the ice road the shore.

Development of Work Sheet Entries

Work Sheet #1: Initial Conditions

This is a massive spill of 10,000 barrels of crude per day that continues for a period of 30 days before the well can be controlled. In this scenario the well is not ignited intentionally and it does not ignite accidentally during the entire period of the spill.

Initial Conditions

Items 1 through 5 are standard oil properties obtained from the producing company. Since slick thicknesses vary considerably, they are described individually in the oil spill budget. Combustibility would be excellent in large accumulations of oil. In fact, there is great danger that the oil could ignite at any time.

Environmental Conditions

Item 9 shows that there are two prevailing wind directions that are nearly opposite. The winds are NE to E 40% of the time and then shift to SW to W 36% of the time. The remaining 24% of the time the winds are nearly evenly distributed over all other directions.

The air temperature (item 10) has an average for March of -28°C. This will significantly chill the escaping oil. The water temperature under the ice is probably close to -2°C, and although the ice temperature is not known, it is probably around -20°C. Items 13 through 16 are not significant for this season.

Ice conditions in item 18 describe the heavy fast ice that is in place in late winter. The fast ice is likely to be about 1.8 m thick and marked by pressure ridges about 0.6 m high. In this nearshore area the pressure ridges are not nearly as high as other ridges may be that are farther from shore. Nearshore pressure ridges in this area have been observed to have a frequency of about 16 per nautical mile which is about 8.6 per km (2).

There is precipitation in the form of snow about 2.5% of the time. The wind causes the snow to accumulate in drifts 40 cm deep and about 9 m crest to crest (3). For this scenario the drifts are assumed to be 6 m wide and have 3 m of clear ice between the rows.

Item 19 shows that visibility is reduced by fog 10% of the time, and when the winds are from the SW,

the visibility is at least somewhat restricted most of the time. Daylight is limited in March. Figure 5.3.1 shows that there is 11 hours of daylight and 3 hours of twilight.

Work Sheet #2: Physical Properties After Weathering

Because this is a long term spill, physical properties are only shown for the 10 day increment and only for the thickest oil accumulation recorded in the physical properties charts.

Figure 2.1.4 shows that at low temperatures and in 10 to 15 kts of wind about 12.5% of the oil will evaporate in 10 days. The evaporation curves become very flat at this point indicating that evaporation will be very slow for the period after the initial 10 days.

Figure 2.2.4 shows that in 10 days at -20°C viscosity will rise to 30,000 cps. This means the oil is in the semisolid range. The pour point will be +12°C, which means that the oil is very viscous. The density of the oil is also quite high. This will not be important until the oil enters the water at break-up.

Work Sheet #3: Oil Spill Budget

Because of the complexity of the distribution of the oil during the blowout, a diagram will be used for this scenario instead of the tabular format used in the other scenarios.

The outer circle on Work Sheet 3 shows the average distrubution of winds during March. The figure shows that the winds tend to be predominately in two opposing sectors, E to NE and W to SW. The remaining winds are nearly equally distributed in all other directions.

Before continuing with a description of the oil around the drill pad, it is important to emphasize the significance of the air temperature and the ice temperature on the oil. North Slope operators report that crude oil spilled in mid-winter, as in this scenario, will set up and harden into a solid in two to three hours. Therefore, oil flowing into a reserve pit or in the vicinity of the drill pad can be expected to harden quickly. The high temperature of the oil leaving the well is expected to have little effect on oil behavior because the cold air temperatures quickly lower this temperature. The oil spilled on the drill pad will seep into the gravel, but the cold temperatures and frozen ground under the top gravel layer are expected to slow, and eventually stop, this vertical movement. Lighter oil particles carried beyond the drill pad boundaries are expected to harden during their fall and appear as brown "sleet" as they strike the ground. The smallest oil particles will continue to be carried by the wind.

The distribution of oil around the spill area is mostly a function of the wind conditions and the particle size distribution of the oil leaving the well. For this blowout it is assumed that 60% of the particles are greater than 0.5 mm, 25% are greater than 0.15 mm, and 15% are less than 0.15 mm. Figure 3.6.4 shows that in a 15 knot wind, particles with a radius of 0.15 mm and greater will land within 100 m of the well. This is basically on the drill pad, and it accounts for about 85% of the oil. Particles with a radius of less than 0.15 mm will be distributed out to about 928 m.

First, consider the amount of oil that sinks into the gravel pad. Assuming that the gravel is raised about 60 cm above the permafrost level, and that the porosity of the gravel is 0.15, the gravel pad could

be expected to hold about 20,000 barrels of oil.

Next consider the effects of evaporation. Figure 2.1.4 shows that the evaporation in 10 days for a thick North Slope crude is about 12.5%. The evaporation process in this scenario is much more complicated than the simple condition of wind blowing over a flat accumulation of oil. On the pad, the oil accumulations will be extremely thick so that there will be less surface exposed for evaporation than is assumed for these evaporation curves. On the other hand, there is significant exposure of the oil particles to evaporation as they leave the well. Since these conflicting processes cannot be easily resolved, a flat rate of 12.5% evaporation was used for all oil accumulations and airborne particulates.

The figure on Work Sheet 3 shows the approximate distribution of oil around the drill pad. The accumulations of oil in each of these sectors represents all of the oil that accumulates in the entire 30 day period less a standard evaporation factor of 12.5%.

The accumulation of oil on the pad (within the 100 m circle) is extremely heavy in the NE and SW sectors because of the prevailing winds. The accumulation of oil of 9 m shown on the diagram is very difficult to visualize, however, this depth results from the assumption that most of the oil accumulates very close to the well. Since it is very difficult to forsee the ultimate results of a disaster, this diagram simply accounts for the oil that is being released and assumes that a large percentage of it remains close to the source. Of course the accumulations are not so large at first, but if no response action is possible and the well does not ignite, the accumulations are bound to become very thick indeed.

The areas to the NE and SW, 100 to 150 m from the center of the pad, also have heavy accumulations of oil. But in these areas there is also a snow cover. The snow has been described on Work Sheet 1 as drifts 40 cm deep aligned with the prevailing wind direction (NE and SW) with crests 9 m apart and areas of relatively clear ice 3 m wide between. Since it is estimated that the oil accumulation in this area will be deeper than the snow drifts, the entire area will be covered with oil. This means the area will have saturated snow drifts, relatively clear oil between the drifts, and a layer of a few centimeters of oil covering the entire area.

In the areas to the NE and SW 150 to 928 m from the center, the snow does not become saturated and the accumulations on the clear ice are much less than those close to the pad. These accumulations will be in the range of 4 to 5 mm.

In the NW and SE sectors, spill accumulations are exactly alike because wind conditions are equal and opposite. In the area from 100 to 150 m from the center, the snow does not become saturated but there is a heavy accumulation of 22 mm on the ice. In the sector from 150 to 928 m oiling is much lighter and there is only 0.5 mm on the ice.

The total volume estimated to be in each sector is shown on the Work Sheet, and in the areas off the pad, the amount of oil that is in the snow and the amount that is on the ice is shown separately.

The preceding spill behavior model must be considered only as a best estimate of what might occur in the case of a blowout. The weakest part of the analysis occurs in the assumption of the distribution of

particle size. Better information is needed concerning this distribution in order to have greater confidence in predicting the way that the oil will be distributed on the ice in the spill area. Attempting to develop a single particle size distribution for the oil/air medium is far too simplistic an approach to a much more complicated problem. There are likely to be a number of possible particle size distributions that depend on the conditions at the blowout. Operators in the field have reported observing blowout conditions in which the heaviest deposits of oil are close to the well, similar to the situation for this scenario. Other observers report blowouts in which virtually no oil falls within a radius of about 150 m of the well. That is, the heaviest deposits form an annulus around the well rather than a thick deposit at the well site. That is the inverse of the situation we describe in this scenario. In short, the prediction of the distribution of oil around a surface blowout is not a well developed disipline.

The OSC should not necessarily plot the distrubution of oil around a blowout using the methods related here. The best way would be to measure accumulations on the ice and determine the saturation level of the snow, then use these measurements to estimate the spill distribution. However, there could be problems with making measurements. It may not be safe to approach the blowout in areas where measurements should be made. Weather conditions may also make field observations almost impossible. If it is not possible to make measurements, then it may be useful to use Figure 3.5.3 to determine the holding capacity of the snow and measure, or estimate the amount of oil pooled on the ice, in order to determine an approximate amount of oil in the spill area.

Work Sheet #4: Spill Volume Remaining

This Sheet shows a plot of the volume of oil remaining over a period of 30 days. Although most of the oil remains on the pad, that amount appears to be somewhat exaggerated visually because of the log scale used on the vertical axis.

Work Sheet #5: Evaporation Rate

The evaporation rate is assumed to be 12.5% for all accumulations of oil; therefore Work Sheet 5 is not included.

Work Sheet #6: Spreading on Open Water

This is a winter fast ice scenario, but spreading on open water will occur at break-up. This Work Sheet therefore describes what is expected to happen as the ice melts in the spring.

Since the spill occurred many months earlier, it is now necessary to determine how much oil remains in place to spread when break-up finally occurs. For as long as the ice remains safe in the spring, large quantities of this oil will be scraped up with dozers and removed with trucks. However, a wide area has been oiled. Some of the oil will be inaccessible to recovery, and some may also be left because there is simply not enough time available to haul it off. In any case, regardless of the intensity of the spill response effort, a quantity of oil can be expected to remain when break-up finally comes. Since the extent of the response effort has not been estimated, no attempt will be made to assess how much remains. This Work Sheet therefore just tracks the path of movement, not the amount that is moved.

As the days warm up, the change of albedo in the heavily oiled areas will accelerate melting of the ice. Some observers believe that in extreme

cases the melting could progress at a rate that is two or three weeks ahead of areas that have not been blackened with oil.

Figure 1.3 (Section 1) shows how entire offshore areas become covered with melt water before break-up. As this happens, the spilled oil will float and become mobile. As noted previously in Section 3.5.3, the oil is likely to settle into melt pools. When the melting in the pools extends all the way through ice and the pool comes in contact with the sea, whirlpools may form that can jettison the oil to a depth of one or two meters below the ice. Oil and water flowing between adjacent melt pools can supply new fluid for these whirl pools. During the melting season the oil will move with the water from the melting ice; it will move from pool to pool with the water; it will follow the vortex flow of the water down through the ice; it will follow the water spilling off the ice into leads; and it may even be blown by the wind over the water pooled on the ice. In short, at break-up the OSC will be faced with a highly dynamic, fast moving spill situation.

There will be no fixed spill radius as the oil enters the water at break-up. The viscous accumulations of oil have already been partitioned many times when the oil was resident on the ice. The oil will be further partitioned as it begins to float on the surface of the melt-water on the ice, as it is jettisoned under the ice in melt vortices, and as it is carried off the ice into opening leads. Oil patches can be expected to be thick and could have almost any surface dimension from particles of millimeter size to large chunks one or several meters across. The overall size of this aggregation will be something like 2 km across, because that was the approximate radius of the original contaminated area. (The volume of oil spilled would be reduced by the cleanup effort.) This radius could be expanded considerably, however, as a result of the oil being carried off with moving ice or moving outward in open leads rather than in the general direction of the shoreline.

The spill drift picture, shown in Figure 5.4.8, is nearly identical to that of the diesel spill in Scenario 1. The differences are that the time of the beginning of that movement is not known because it depends on the start of break-up. Also the spill movement can be expected to be highly confused as break-up begins. The oil will tend to move off the ice as leads open up, and there will be some ice movement with the wind. As break-up progresses, open water areas will increase. It is likely that large amounts of oil will accumulate in the open water and may be partially restrained by the large pieces of ice that remain. There would also be some net drift, with the ice and oil all moving together at a fairly low rate. This phase would provide an opportunity to recover some of the drifting oil if a response vessel can be obtained that is capable of navigating among the heavy pieces of melting ice.

By the last week in July or the first week in August, the drifting ice should be gone and the open water drift phase of spill movement will begin.

Figure 5.4.8 shows the time required to reach the shoreline after the spill begins drifting in open water. In fact these times may be extended considerably because of the confused phase during break-up when the oil is moving among the pieces of melting ice. Spill movement will finally begin, however, and based on prevailing winds and currents, it is likely to be westward.

Now consider item 6 of Work Sheet 6. Figure 5.4.9 shows that the first point of land the spill will contact is the west end of Long Island and all of Cottle Island. Long Island is entirely in Retention Index 3, a non-vegetated barrier, and Cottle Island is a non-vegetated barrier with some steep beaches and bluffs. (Figure 5.4.9 is taken from Section 4 of this Field Guide.) These are both fairly high wave energy areas where spill residence time is likely to be less than a year and spill damage is expected to be low. Because of these features, the general advice in Section 4 is to stand off and let nature do the cleaning. This advice should probably be modified somewhat because of the size of the spill. A light coating of diesel on the barrier island is probably best left alone. It won't do much damage and it is likely to be completely dissipated in a year. If heavy masses of highly weathered crude are deposited on the barrier islands, the situation becomes different. This crude might also be removed in a year, but the same wave and current conditions that would dissipate arctic diesel in the water column may only carry the viscous crude away to possibly pollute another area. In this case, then, the OSC should seriously consider cleaning a heavily oiled gravel island to remove the oil from the environment.

The situation for the oil moving between the gravel islands into the lagoon is about the same as the scenario for the arctic diesel except that for weathered crude the impact in the lagoon is likely to be much more severe. With the arctic diesel there is the threat of a long term residence in the sensitive areas of the lagoon shoreline and the marshes. With massive amounts of highly weathered, thick crude, the problem is more serious. The threat is now similar to the METULA spill event in the Strait of Magellan described in Section 4.2. There is some danger of burying this shoreline under a heavy layer of asphalted pavement that would become a permanent feature of the coastline.

The remaining parts of Work Sheet 6 would be completed as before. The OSC would determine the distance to the pack ice and estimate the drift. The parts of the spill that became lodged along the edge of the pack ice could be transported a considerable distance from the spill site, probably westward.

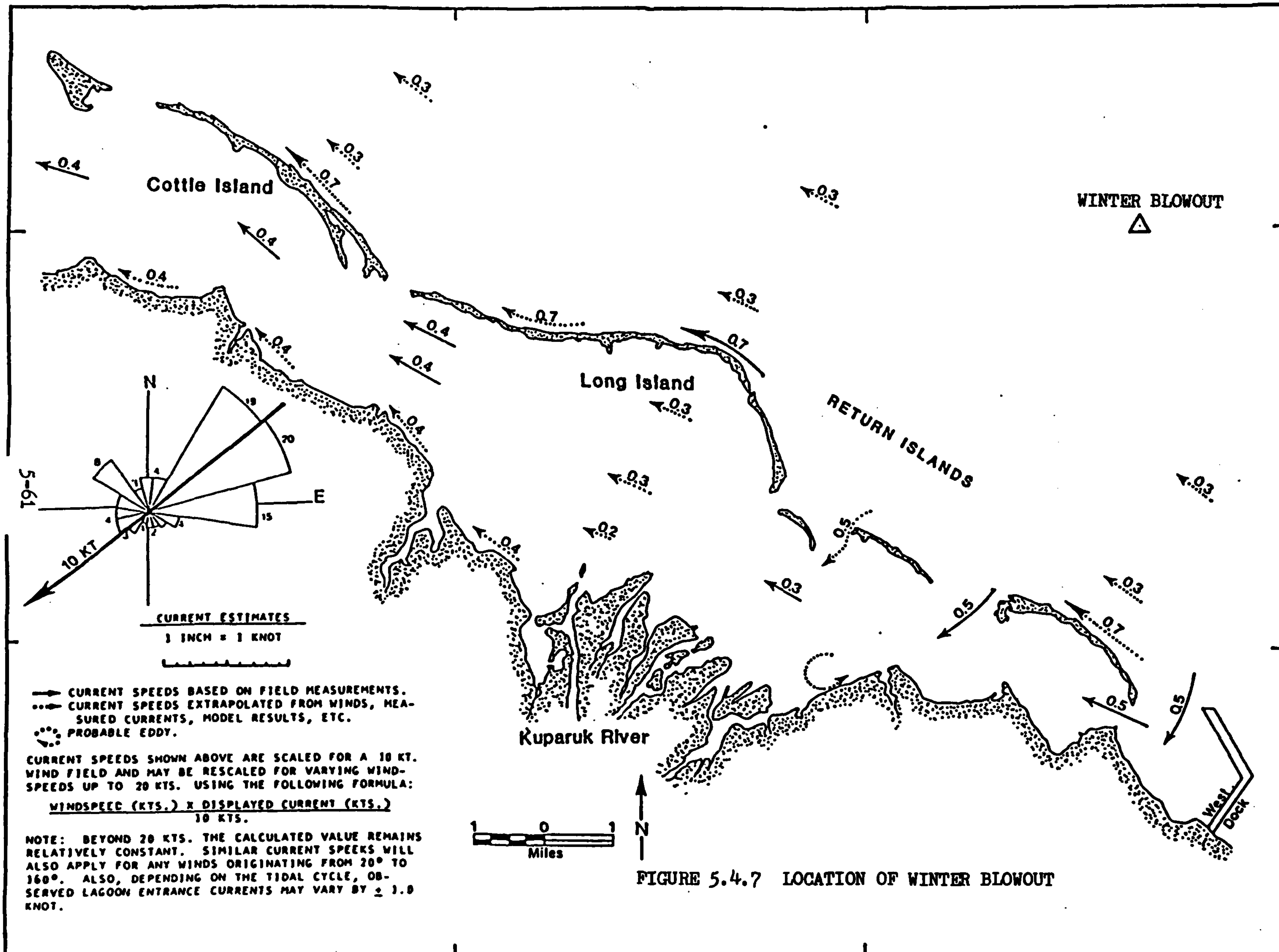


FIGURE 5.4.7 LOCATION OF WINTER BLOWOUT

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 3

DATE AND TIME SPILL BEGAN 15 March 1200 Local

SPILL LOCATION 70-30N 148-35W TYPE OIL North Slope Crude

AMOUNT SPILLED 10,000 bbl/day for 30 days--300,000 bbl

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) 60°C (well head) 2) SP. GRAVITY (g/cc) 0.895

3) VISCOSITY (cp) 35.0 4) POUR POINT (°C) -9.4°C 5) SOLUBILITY 29.2g/m³

6) SLICK THICKNESS (1) (See spill budget) (3)
(2) (4)

7) COMBUSTIBILITY Excellent in large accumulations of oil.

8) EMULSIFICATION None

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) 40% winds NE to E, 15 kts; 36% SW to W, 13 kts, March; average 055 T/10 kts; range E/10 kts to NE/5 kts August.

10) TEMPERATURE (°C): AIR -28°C (-18°F) 11) WATER -2°C 12) ICE -20°C

13) WATER DEPTH (m) 11 m 14) WAVE HEIGHT (m) None 15) CURRENTS Under ice

16) TIDE (m) --- 17) STORM SURGE HEIGHT ABOVE MSL (m) ---

18) ICE CONDITIONS Fast ice 1.8 m (6 ft) thick; pressure ridges 0.6 m high, frequency of 16/NM or 8.6/km. Radial distance of 100 to 150 m, 0.4 chance of a pressure ridge; radial distance of 150 to 928 m, 6.7 pressure ridges.

19) PRECIPITATION 2.5% of time, snow

20) VISIBILITY Fog 10% of time
Wind NE to E, Vis <2 nm 12% of time.
Wind SW to W, Vis <15 NM 85% of time

21) DAYLIGHT (HRS) 11, twilight 3

SPILL BEHAVIOR WORK SHEET #2

PHYSICAL PROPERTIES AFTER WEATHERING

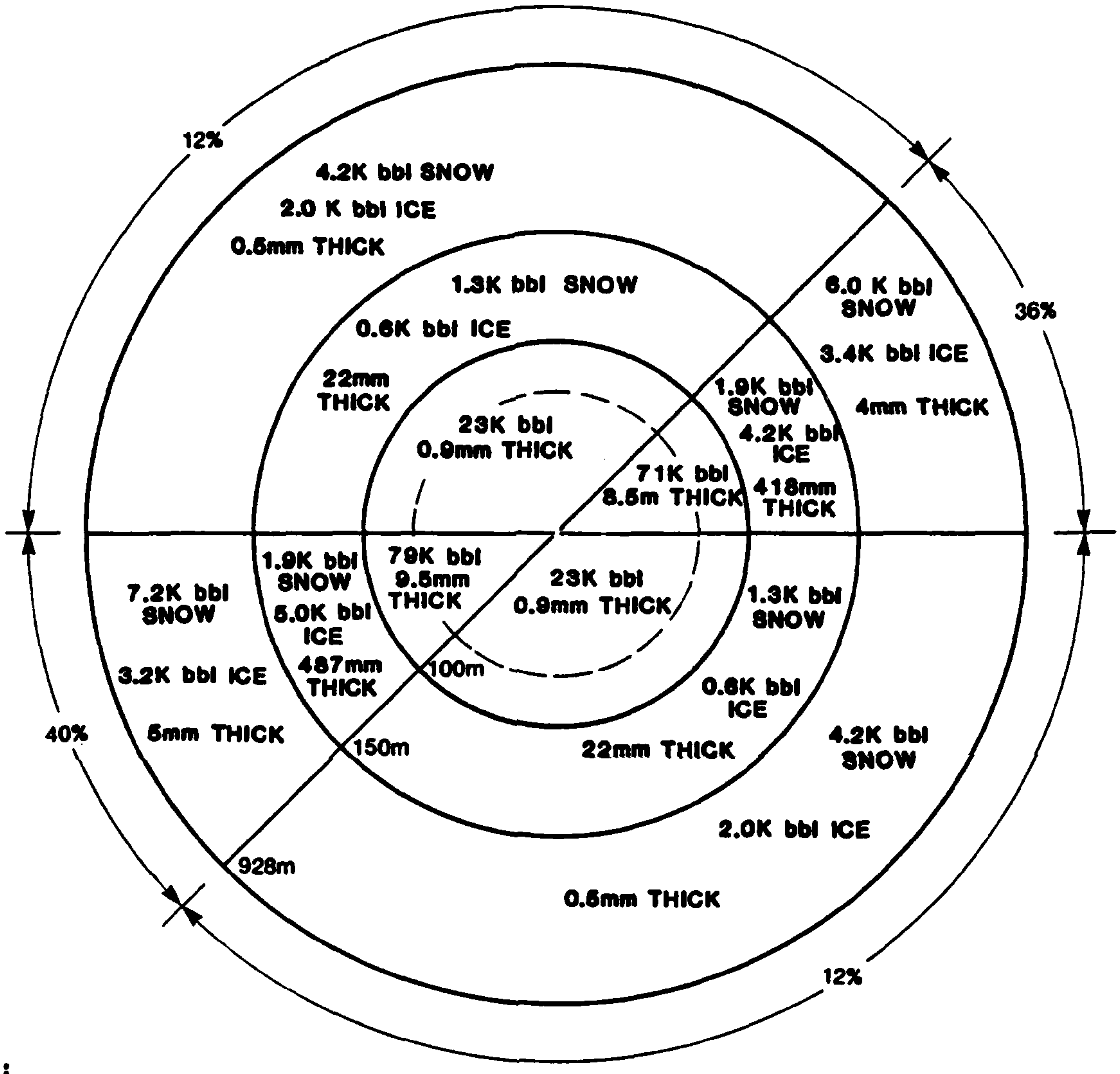
1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)											87.5	
4) VISCOSITY (cps)											30,000	
5) POUR POINT (°C)											+12	
6) DENSITY (g/cc)											0.94	
7) SOLUBILITY (g/m^3)											2	

REMARKS: ______________________________

WORK SHEET #3 OIL SPILL BUDGET

DISTRIBUTION OF OIL AROUND BLOWOUT

SCENARIO 3



NOTES:

1. Area divided into three radial sections, based on oil particle size distribution: a) 0-100 m, large particle (drill pad area); b) 100-150 m, moderate size particles; c) 150-928 m, fine particles.

2. Distribution pattern based on prevailing winds; 40% of winds from NE, 36% from SW, 24% about equally divided from other directions.

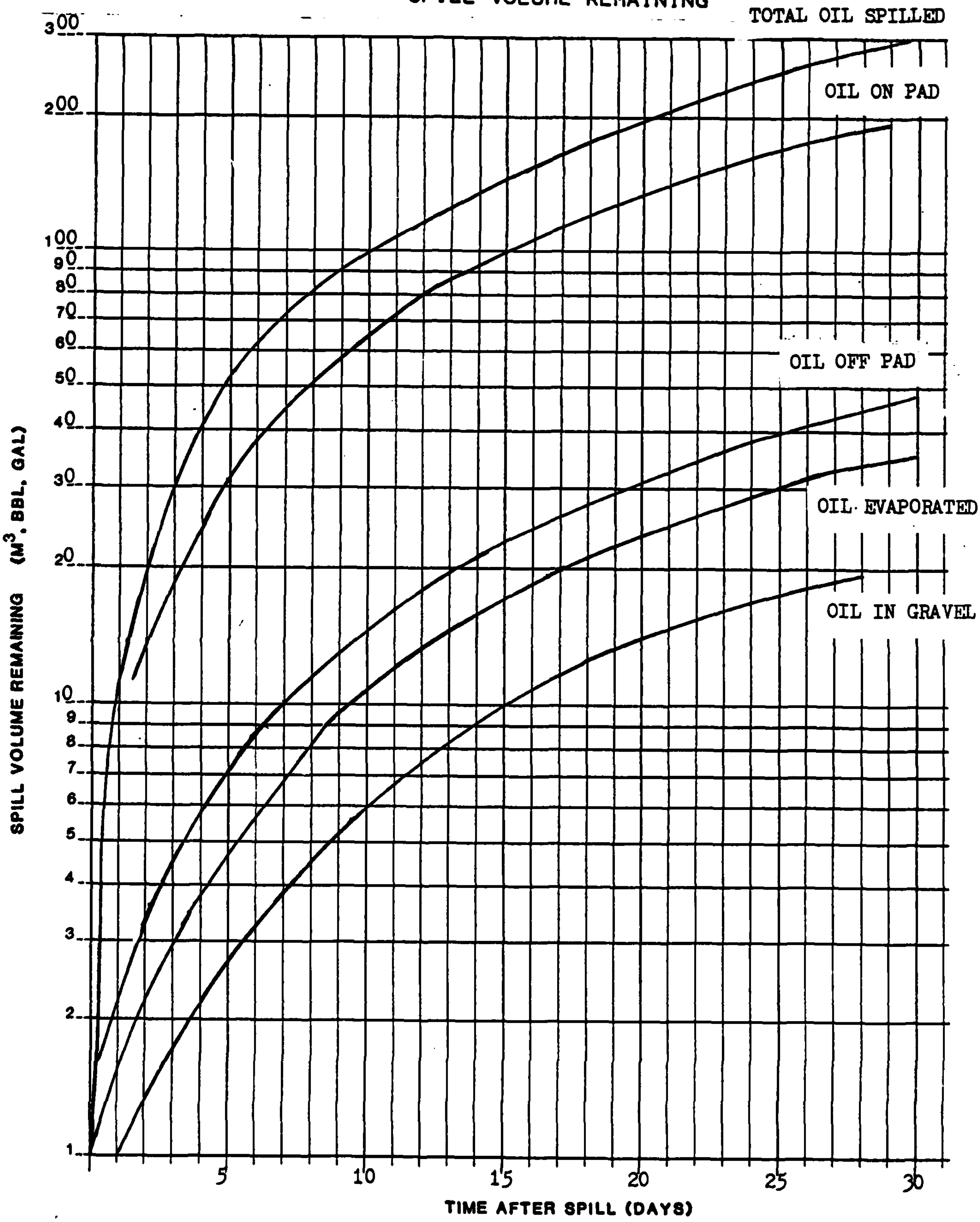
3. Snow outside the pad area forms windrows spaced 9 m apart with 3 m relatively clear ice between; snow 40 cm deep (2).

4. In the NE and SW sectors, 100 to 150 m from the center, the snow becomes saturated so there are large accumulations of oil on the ice, which are contained by the snow banks.

5. All thicknesses of oil refer to oil on the pad or oil on ice; oil in snow is absorbed and does not have a specific thickness.

SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING



SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER
SCENARIO 3

	THICK SLICK	THIN SLICK
1) SPILL RADIUS (m):	1,000	
2) SLICK THICKNESS (mm):	variable	

3) SPILL DRIFT VECTOR: AVERAGE 270°T/0.5 kts RANGE 262°T/0.45 kts 285°T/0.45 kts

4) DISTANCE TO SHORELINE (NM): MAX 15.6 MIN 9.4

TIME TO REACH SHORELINE (HRS): MAX 28 MIN 20

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST ____ LATEST ____ Depends on breakup

6) LENGTH OF SHORELINE CONTAMINATED (NM): ____

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	indefinite
2	3.2	6	
3	4.4	7	
4		8	0.6

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- o SHORELINE TYPE 2) Steep beaches and bluffs 3) Non-vegetated barriers 5) Lagoon facing mainland shores, 8) Marsh
- o IMPACT 2) Low waves keep oil off beach, 3) low species density, clean in about 1 year. 5) Slow removal because of low wave energy; oil could be released later to other beaches
- o PERSISTENCE 2) Removed by waves, off in 1 or 2 years, 3) about 1 year 5) Could persist for years because of low transport rate, 8) Virtually permanent after evaporation loss
- o PROTECTION 2) Offshore boom, 3) Offshore boom, 5) & 8) Boom off lagoon entrance.
- o CLEAN-UP 2) Clean sandy beaches, 3) Remove large accumulations of oil 5) Recover oil collected in boom; clean beach to protect tundra margin, 8) Clean up likely to be counter productive

7) DISTANCE TO PACK ICE (NM): 20 TIME TO REACH PACK ICE(HRS) MAX 56 MIN 40

8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST ____ LATEST ____ Depends on breakup

9) LENGTH OF PACK ICE CONTAMINATED (NM) 5

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) West 6./ nm/day

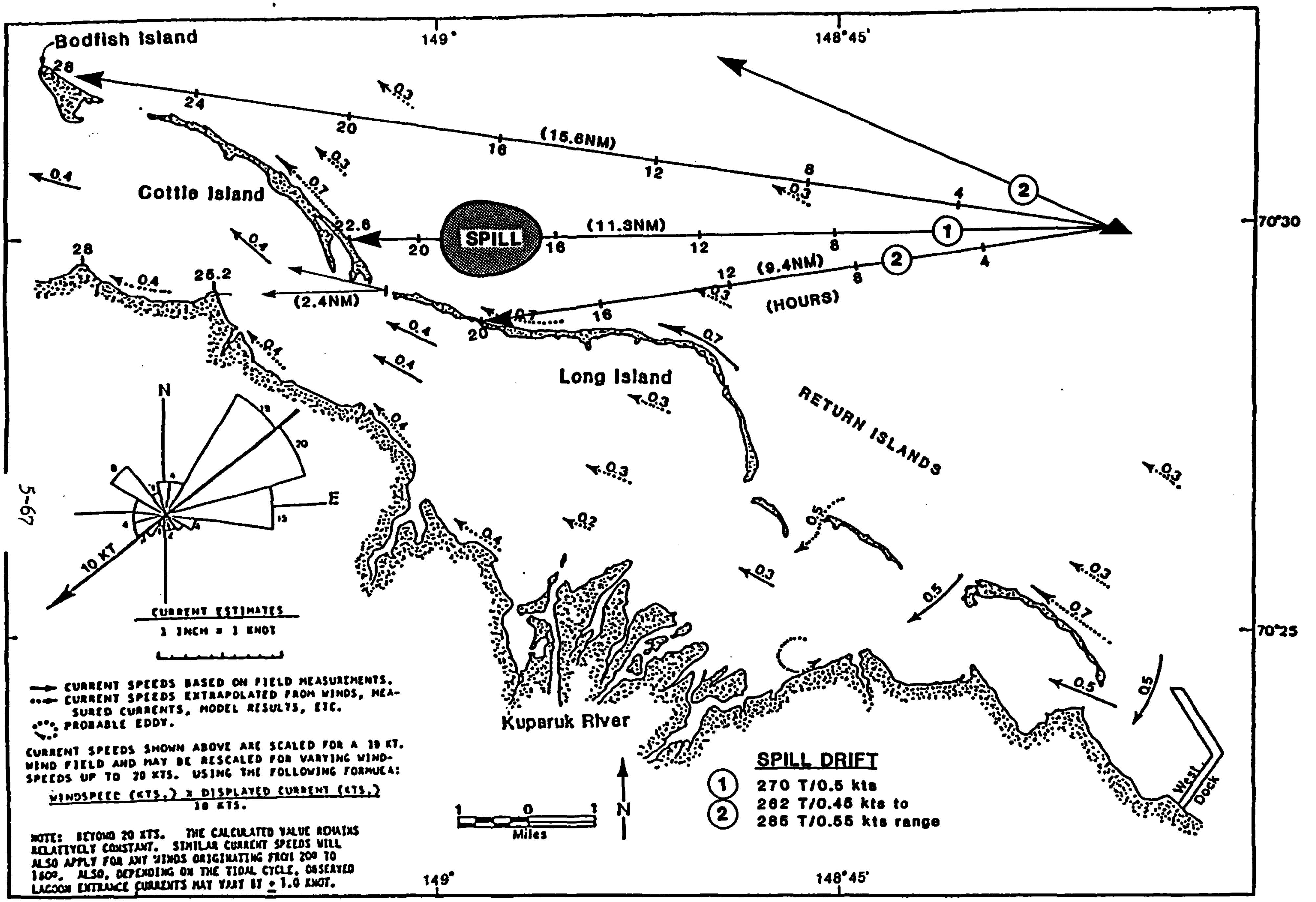


FIGURE 5.4.8 SPILL DRIFT, BLOWOUT

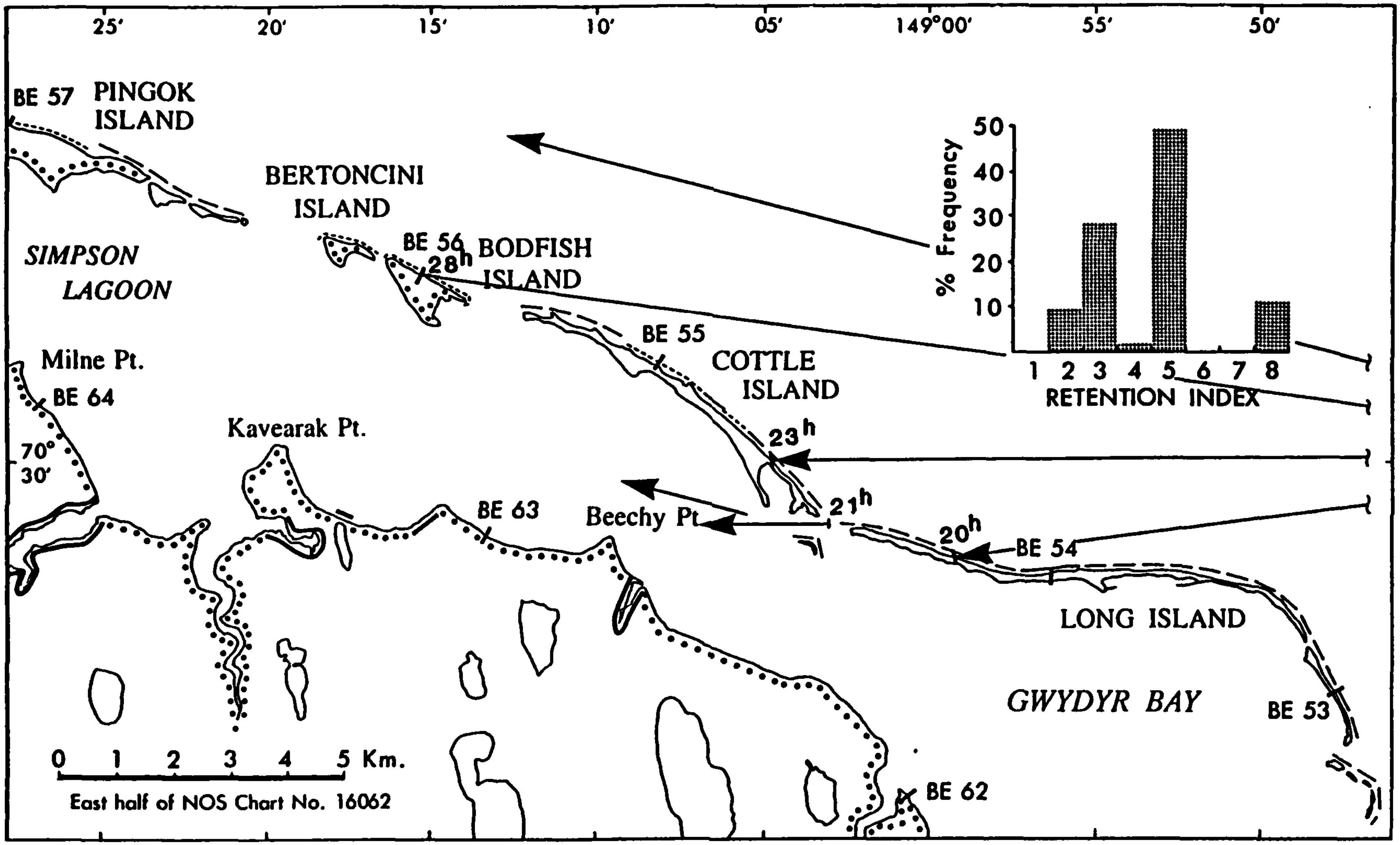


FIGURE 5.4.9 SPILL IMPACT, BLOWOUT

5.4.4 SCENARIO 4 - WINTER BLOWOUT WITH IGNITION

About noon on 15 March a well being drilled from a gravel island blows out of control. After carefully reviewing alternatives for controlling the well, a decision was made to ignite the well early on the fourth day.

Spill Location: The spill occurs on a gravel island at 70-30N, 148-35W, about 5 nm east-northeast of the north end of Long Island. Figure 5.4.10 shows the location of the spill.

Season: Fast ice, during the middle of March.

Spill Description: At about 1200 local time a well being drilled from a gravel island blows out of control. Initial efforts by the drilling crew to control the well are unsuccessful, and the resulting blowout is estimated at 10,000 barrels per day. The gas and evaporation of the lighter ends of the crude oil present an explosion and fire hazard in the immediate area of the blowout. Because of this danger and the prospect of heavy accumulations of oil in the vicinity of the pad, a decision was made to ignite the well early on the fourth day of the spill.

Development of Work Sheet Entries

Work Sheet #1: Initial Conditions

This is a massive spill of 10,000 barrels of crude per day that continues for a period of 30 days before the well can be controlled. The well is ignited on the fourth day of the spill and it is estimated that the combustion is 90% effective.

Initial Conditions

Items 1 through 5 are standard oil properties obtained from the producing company. Since slick thicknesses vary considerably, they are described individually in the oil spill budget. Combustibility conditions are excellent so that a very high percentage of the oil and gas released above ground directly into the the air stream are burned. In addition, larger accumulations of oil on the pad and the surrounding ice are also burned away. It is estimated that the overall burn efficiency is 90%.

Environmental Conditions

Item 9 shows that there are two prevailing wind directions that are nearly opposite. In March the winds are NE to E 40% of the time and then shift to SW to W 36% of the time. The remaining 24% of the winds are nearly evenly distributed over all other directions. In August when the open water drift occurs, average winds are 055° T at 10 kts and range from east at 10 kts to NE at 5 kts.

The air temperature, item 10, has an average value for March of -28°C. This will significantly chill the escaping oil. The water temperature under the ice is probably close to -2°C, and although the ice temperature is not known, it is probably around -20°C. Items 13 through 16 are not significant for this season.

Ice conditions in item 18 describe the heavy fast ice that is in place in late winter. The fast ice is likely to be about 1.8 m thick and marked by pressure ridges about 0.6 m high. In this nearshore area the pressure ridges are not nearly as high as other ridges may be that are farther from shore. Nearshore pressure ridges in this area have been observed to have a frequency of about 16 per nautical mile which is about 8.6 per km (2).

There is precipitation in the

form of snow about 2.5% of the time. This results in an accumulation of about 40 cm in drifts oriented with the wind that are about 9 m crest to crest (3). For this scenario these drifts are assumed to be 6 m wide and have 3 m of clear ice between the rows.

Item 19 shows that visibility is reduced by fog 10% of the time, and when the winds are from the SW, the visibility is at least somewhat restricted most of the time. Daylight is not limited in March, since Figure 5.3.1 shows that there are 11 hours of daylight and 3 hours of twilight.

Work Sheet #2: Physical Properties After Weathering

Because the well has been ignited, the physical properties will be far more dependent on the burn process than on normal weathering in the atmosphere. Unfortunately, the physical properties of the residues of burning oil are not well known. Burn tests have been performed in the Arctic, but the physical properties of the residues of these burns have not been recorded. The residues of burn in the various tests have been described as tarry clumps firm enough to be picked up with a shovel (4). In one case the residue was described as a tarry sheet that could be lifted by grabbing a corner. The results of the Balaena Bay tests indicated that the residues had a specific gravity of less than one and that there was no evidence of this residue sinking in water.

In spite of the assurances that the residues did not sink, it must be assumed that the specific gravity of the products of a burn is very close to one, and that the reserve buoyancy is very low. As a result, there is a potential for the residues of a burn to sink.

The remaining physical properties can only be described in general terms. Viscosity would be very high and winter temperatures would be well below the pour point of the burn residues. Knowing these general properties of the spilled product is adequate to determine the fate of the spill in the environment.

Work Sheet #3: Oil Spill Budget

Because of the complexity of the distribution of the oil during the blowout, a diagram will be used for this scenario instead of the tabular format used in the other scenarios.

The diagram on Work Sheet 3 shows the average distrubution of winds during March. The figure shows that the winds tend to be predominately from two opposing sectors, E to NE and W to SW. The remaining winds are nearly equally distrubuted in all other directions.

The distribution of oil around the spill area is assumed to have the same basic pattern as in Scenario 3 except that after the fourth day 90% of the oil is consumed by burning. This is not just the oil that comes out after the fourth day. On the contrary, the oil on the pad and on the ice is also expected to burn with an efficiency of 90%. The oil that is absorbed in the pad is the only part of the spill that is not expected to be exposed to burning. Work Sheet 4 in Scenario 3 shows that about 2,700 barrels of oil is expected to accumulate in the pad in a period of 4 days, therefore this is the only amount that is not subject to burning.

The effects of evaporation are not considered in this scenario because the amount of oil consumed by burning is so large. Ninety percent of the oil from the blowout is gone. It doesn't really matter if some of that loss is due to evaporation.

The figure on Work Sheet 3 shows the approximate distribution of oil around the drill pad. The accumulations of oil in each of these sectors represents all of the oil that accumulates in the entire 30 day period less the 90% that is assumed to be burned. Work Sheet 3 shows the amount of oil that is expected to collect in each sector around the drill pad and the thickness of the accumulation. No distinction is made in this case between areas covered with snow or areas of clear ice. The saturated snow is also expected to burn so that the residues of the burn are expected to be distributed fairly evenly in all of the areas. As in the case of the blowout without burning, the heaviest accumulations of oil are on the pad to the NE and SW, the directions of the prevailing winds. The accumulations off the pad and in the other sectors are much lighter.

Work Sheet #4: Spill Volume Remaining

This Sheet shows a plot of the volume of oil remaining over a period of 30 days. Note that most of the residue of burning remains on the pad. The best way to determine the volume of residue in the area around the pad is to make measurements. This could not be done while the well is burning, but it should be done as soon as the fire is out and it is safe to enter the area.

Work Sheet #5: Evaporation Rate

Evaporation is not considered.

Work Sheet #6: Spreading on Open Water

This is a winter fast ice scenario, but spreading on open water will occur at break-up. This Work Sheet therefore tracks what is expected to happen as the ice melts in the spring.

The first issue is to determine how much oil remains in place to spread when break-up finally occurs. Although this is not a response scenario, one must in this case account in some way for the the oil that will be removed from the spill site after the blowout has been secured. Even though the well has been ignited, the 10% of the oil that does not burn still leaves fairly large accumulations of oil on the pad and immediately adjacent to the pad. Work Sheet 3 shows accumulations from 4 to 39 cm thick on the pad (inside the 100 m radius) and accumulations of about 2 cm occur NE and SW in the 100 to 150 m radius from the well. In the NW and SE sectors 100 to 150 m from the well the accumulation is about 2.5 mm, and outside these areas the accumulation is very light. For as long as the ice remains safe in the spring, large quantities of this oil will be scraped up with dozers and removed with trucks. Oil accumulations of 2 mm and greater can probably be removed by scraping, but the thinner coating probably cannot be removed with heavy equipment. In any case, regardless of the intensity of the spill response effort, a sizable quantity of oil and residues of burning can be expected to remain when break-up finally comes. Since the extent of the response effort has not been estimated, no attempt will be made to assess how much remains. This Work Sheet will just track the path of movement, not the amount that is moved.

As the days warm up, the change of albedo in the heavily oiled areas will accelerate melting of the ice. Some believe that in extreme cases the melting could progress at a rate that is two or three weeks ahead of areas that have not been blackened with oil.

Figure 1.3 (Section 1) shows how entire offshore areas become covered with water from river run-off

and melting ice before break-up. As this happens, the spilled oil and residues of burning will float and become mobile. The movement of the residues of burning in the water from melting ice may be somewhat different from the weathered crude in the same environment. The physical properties of the residues of burning could be highly variable. Some residues may be highly viscous, but not entirely unlike highly weathered crude, while others may be so hard they resemble pieces of plastic (5). The densities of these residues have not been reported but they are likely to be high. Further, the melt water on the ice comes from snow, river run-off, and the melting surface of first year ice, a combination that will have a low salinity. Since this water pooled on ice is nearly fresh, it will have a lower density than sea water and the relatively dense burn residues are more likely to sink.

Overall, the behavior of the residues of the burn may be somewhat different than the weathered crude described in Scenario 3. The residue of burn will be extremely viscous, and if it has an opportunity to weather for a month or more after the fire is out, it may resemble an asphalt. Visualize what may happen as this heavier residue is released during break-up. The residues of burn may be very cohesive and therefore less likely to break up into smaller pieces when the ice breaks away and the oil is washed into leads. Pieces may be thick and large, and they would be less likely to be released into drain vortices in the ice or in small cracks in the ice.

The pieces of residue from a burn are therefore expected to be larger and heavier than those from crude weathering. The residues of a burn are also likely to have a very high specific gravity so that as they float they may be awash and they may even sink before they reach the shoreline.

There will be no fixed spill radius as the oil and residues of burning enter the water at break-up. Patches of oil and residue of burning can be expected to be thick and could have almost any surface dimension from particles of millimeter size to large chunks one or several meters across. The overall size of this aggregation will be something like 300 m across, because that was the approximate radius of the heavily contaminated area before break-up. This radius could be expanded considerably, however, as a result of the oil being carried off with moving ice or moving outward in open leads rather than in the general direction of the shoreline.

The spill drift picture, shown in Figure 5.4.11, is nearly identical to that of Scenarios 1 and 3. As before, the time of the beginning of the drift is not known because it depends on the start of break-up. Also the spill movement can be expected to be highly confused as break-up begins. The oil and residues of burning will tend to move off the ice as leads open up, and there will be some ice movement with the wind. As break-up progresses, the area of open water will increase. It is likely that large amounts of oil and residues of burning will accumulate in the open water and be virtually contained by the large pieces of ice that remain. There would also be some net drift, with the ice and oil all moving together at a fairly low rate. This phase would provide an opportunity to recover some of the drifting oil and residues of burning if a response vessel can be obtained that is capable of navigating among the heavy pieces of melting ice.

By the last week in July or the first week in August, the drifting ice should be gone and the open water

drift phase of spill movement will begin.

Figure 5.4.11 shows the time required to reach the shoreline once the spill begins drifting in open water. In fact these times may be extended considerably because of the confused phase during break-up when the oil is moving among the pieces of melting ice. The movement will finally begin, however, and based on prevailing winds and currents, it is likely to be westward.

Now consider item 6 of Work Sheet 6. Figure 5.4.12 shows that the first point of land the spill will contact is the west end of Long Island and all of Cottle Island. Long Island is entirely in Retention Index 3, a non-vegetated barrier, and Cottle Island is a non-vegetated barrier with some steep beaches and bluffs. These are both fairly high wave energy areas where spill residence time is likely to be less than a year and spill damage is expected to be low. Because of these features, the general advice in Section 4 is to stand off and let nature do the cleaning. This advice should probably be modified somewhat because of the size of the spill. A light coating of diesel on the barrier island is probably best left alone. It won't do much damage on a non-vegetated barrier island and it will be degraded in the water column as it is washed away by the action of the waves and current. If heavy masses of residues of the burn are deposited on the barrier islands, the situation becomes different. These burn residues may also be removed in a year, but they are likely to be c.rried away by currents and pollute another area instead of being degraded in the water column. In this case, then, the OSC should seriously consider cleaning a heavily oiled gravel island to remove the spilled products from the environment.

The situation for the oil moving between the gravel islands into the lagoon is about the same as the scenario for the weathered crude. As with the weathered crude there is the threat of a long term residence in the sensitive areas of the lagoon shoreline and the marshes. With large amounts of heavy residues from the burn, the environmental problem may be even more severe than for weathered crude. The threat would be similar to the METULA spill event in the Strait of Magellan described in Section 4.2. There is some danger of burying this shoreline under a heavy layer of asphalted pavement that would become a permanent feature of the coastline.

The remaining parts of Work Sheet 6 would be completed as before. The OSC would determine the distance to the pack ice and estimate the drift. The parts of the spill that became lodged along the edge of the pack ice could be transported a considerable distance from the spill site, probably westward.

Work Sheet #7: Plot of Spill Drift

This Work Sheet shows the vector plot used to determine spill drift.

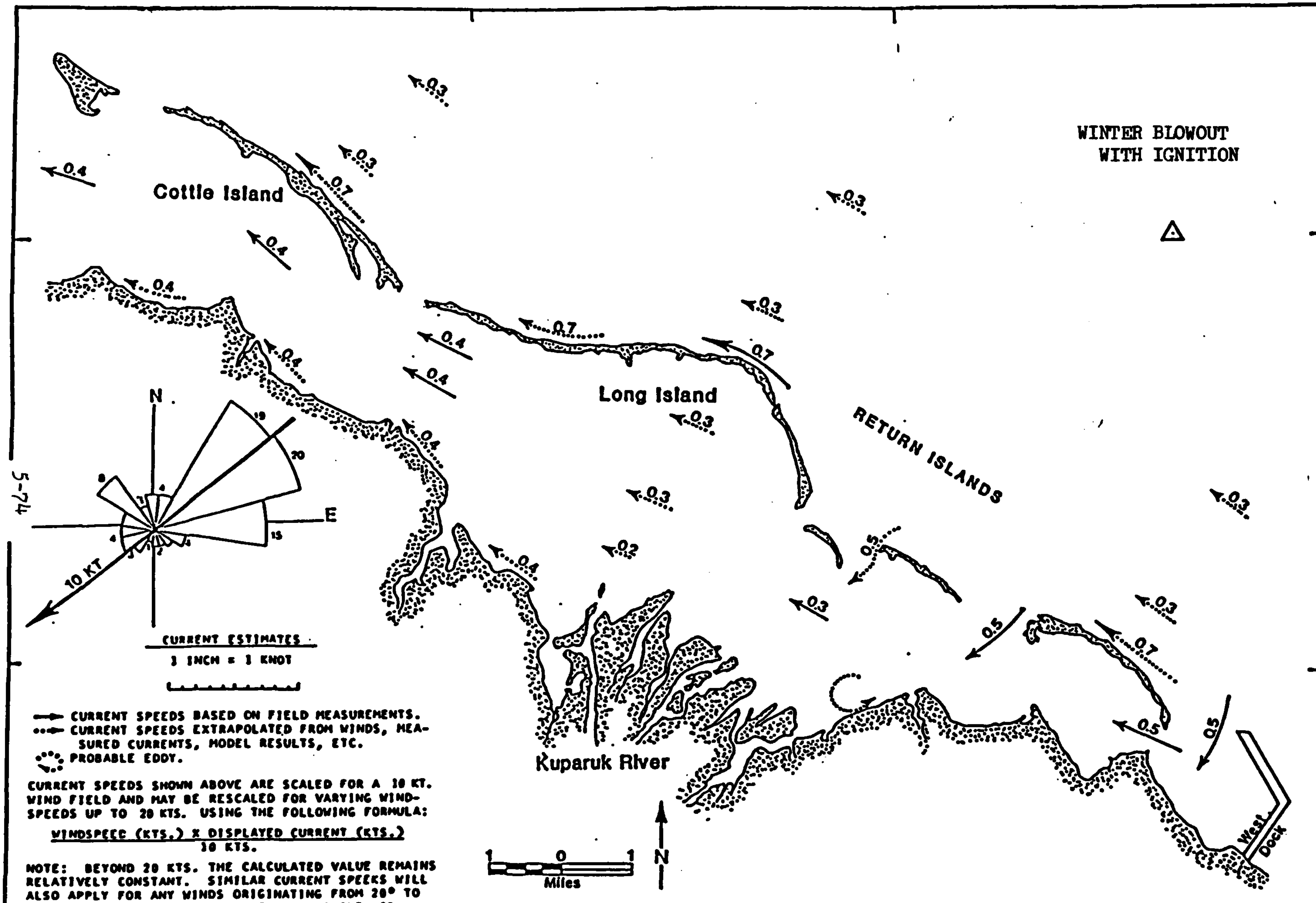


FIGURE 5.4.10 LOCATION OF WINTER BLOWOUT, WITH IGNITION

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 4

DATE AND TIME SPILL BEGAN 15 March 1200 Local

SPILL LOCATION 70-30N 148-35W TYPE OIL North Slope Crude

AMOUNT SPILLED 10,000 bbl/day for 30 days--300,000 bbl

INITIAL OIL CONDITIONS

1) TEMPERATURE (oC) 60°C (well head) 2) SP. GRAVITY (g/cc) 0.895

3) VISCOSITY (cp) 35.0 4) POUR POINT (oC) -9.4°C 5) SOLUBILITY 29.2g/m^3

6) SLICK THICKNESS (1) (See spill budget) (3)
(2) (4)

7) COMBUSTIBILITY Excellent in large accumulations of oil.

8) EMULSIFICATION None

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) 40% winds NE to E, 15 kts; 36% SW to W, 13 kts. March: Average 055°T/10 kts; range E/10 kts to NE/5 kts August.

10) TEMPERATURE (oC): AIR -28°C (-18°F) 11) WATER -2°C 12) ICE -20°C

13) WATER DEPTH (m) 11 m 14) WAVE HEIGHT (m) None 15) CURRENTS Under ice

16) TIDE (m) --- 17) STORM SURGE HEIGHT ABOVE MSL (m) ---

18) ICE CONDITIONS Fast ice 1.8 m (6 ft) thick; pressure ridges 0.6 m high, frequency of 16/NM or 8.6/km. Radial distance of 100 to 150 m, 0.4 chance of a pressure ridge; radial distance of 150 to 928 m, 6.7 pressure ridges.

19) PRECIPITATION 2.5% of time, snow

20) VISIBILITY Fog 10% of time
Wind NE to E, Vis < 2 nm 12% of time.
Wind SW to W, Vis < 15 NM 85% of time

21) DAYLIGHT (HRS) 11, twilight 3

SPILL BEHAVIOR WORK SHEET #2

PHYSICAL PROPERTIES AFTER WEATHERING

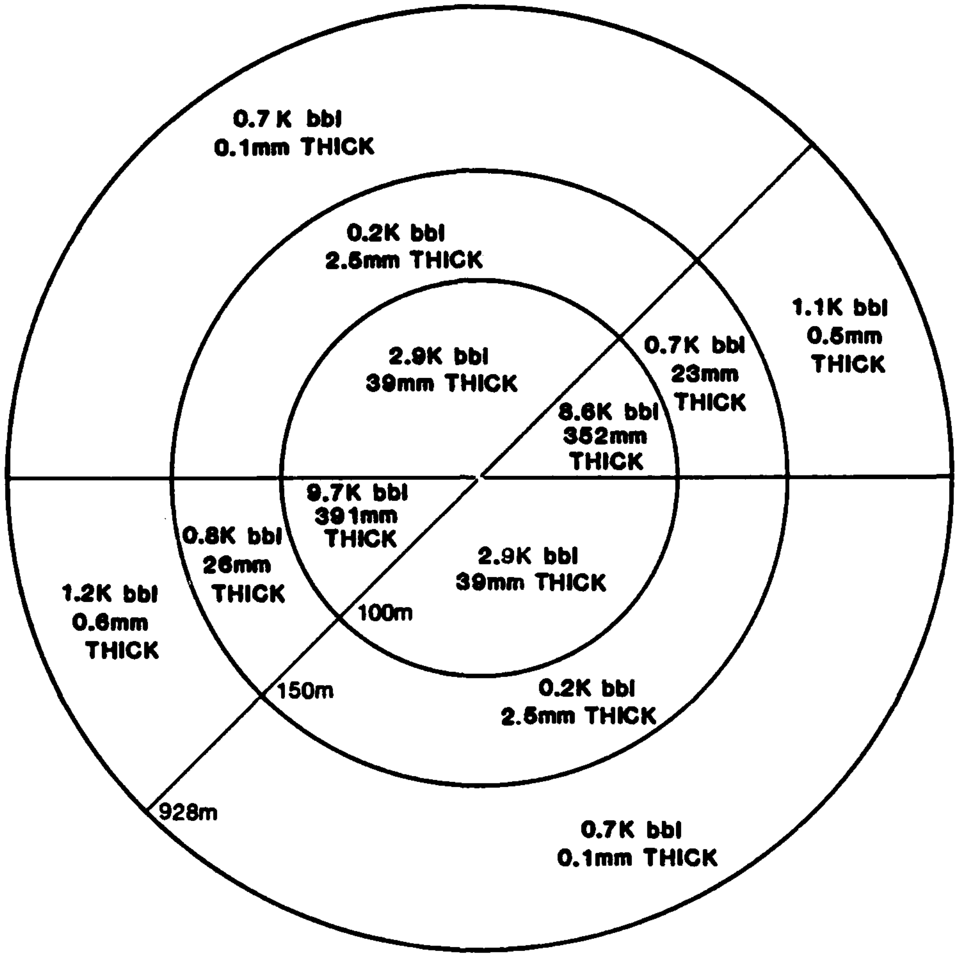
1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)											87.5	
4) VISCOSITY (cps)											30,000	
5) POUR POINT (°C)											+12	
6) DENSITY (g/cc)											0.94	
7) SOLUBILITY (g/m3)											2	

REMARKS: ______________________________

WORK SHEET #3 OIL SPILL BUDGET

DISTRIBUTION OF OIL AROUND BLOWOUT - WITH IGNITION

SCENARIO 4



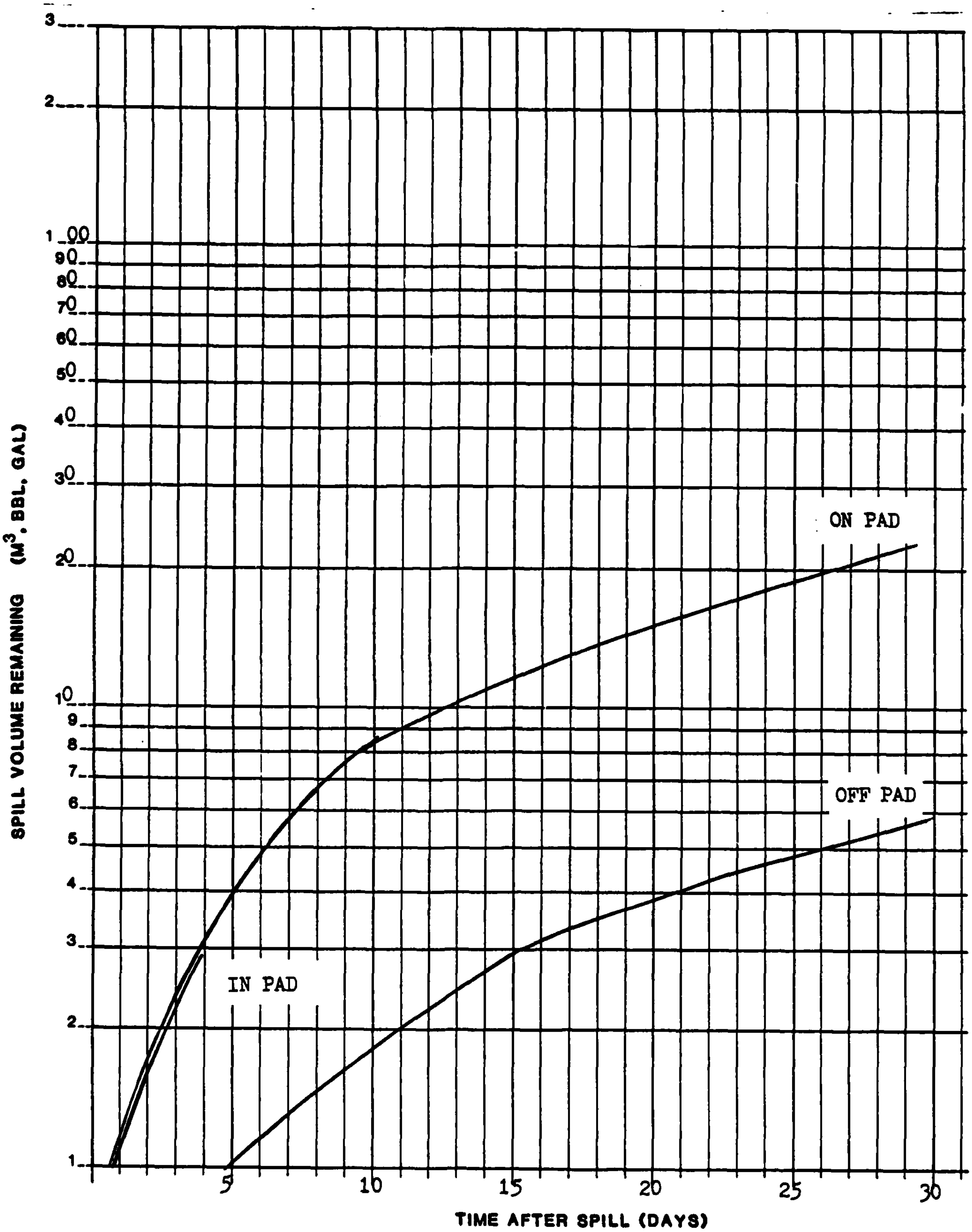
NOTES:

1. Distribution pattern based on prevailing winds; 40% winds from NE, 36% from SW, and 24% equally divided between other directions.

2. Burning is assumed to be uniform regardless of snow cover.

SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING



SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER
SCENARIO 4

		THICK SLICK	THIN SLICK
1)	SPILL RADIUS (m):	1,000	
2)	SLICK THICKNESS (mm):	variable	

3) SPILL DRIFT VECTOR: AVERAGE 270^{o}T/0.5 kts RANGE 262^{o}T/0.45 kts 285^{o}T/0.45 kts

4) DISTANCE TO SHORELINE (NM): MAX 15.6 MIN 9.4
TIME TO REACH SHORELINE (HRS): MAX 28 MIN 20

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST ______ LATEST ______ Depends on breakup

6) LENGTH OF SHORELINE CONTAMINATED (NM): ______
LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	indefinite
2	3.2	6	
3	4.4	7	
4		8	0.6

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- SHORELINE TYPE 2) Steep beaches and bluffs 3) Non-vegetated barriers 5) Lagoon facing mainland shores, 8) Marsh
- IMPACT 2) Low waves keep oil off beach, 3) low species density, clean in about 1 year. 5) Slow removal because of low wave energy; oil could be released later to other beaches
- PERSISTENCE 2) Removed by waves, off in 1 or 2 years, 3) about 1 year 5) Could persist for years because of low transport rate, 8) Virtually permanent after evaporation loss
- PROTECTION 2) Offshore boom, 3) Offshore boom, 5) & 8) Boom off lagoon entrance.
- CLEAN-UP 2) Clean sandy beaches, 3) Remove large accumulations of oil 5) Recover oil collected in boom; clean beach to protect tundra margin, 8) Clean up likely to be counter productive

7) DISTANCE TO PACK ICE (NM): 20 TIME TO REACH PACK ICE(HRS) MAX 56 MIN 40

8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST ______ LATEST ______ Depends on breakup

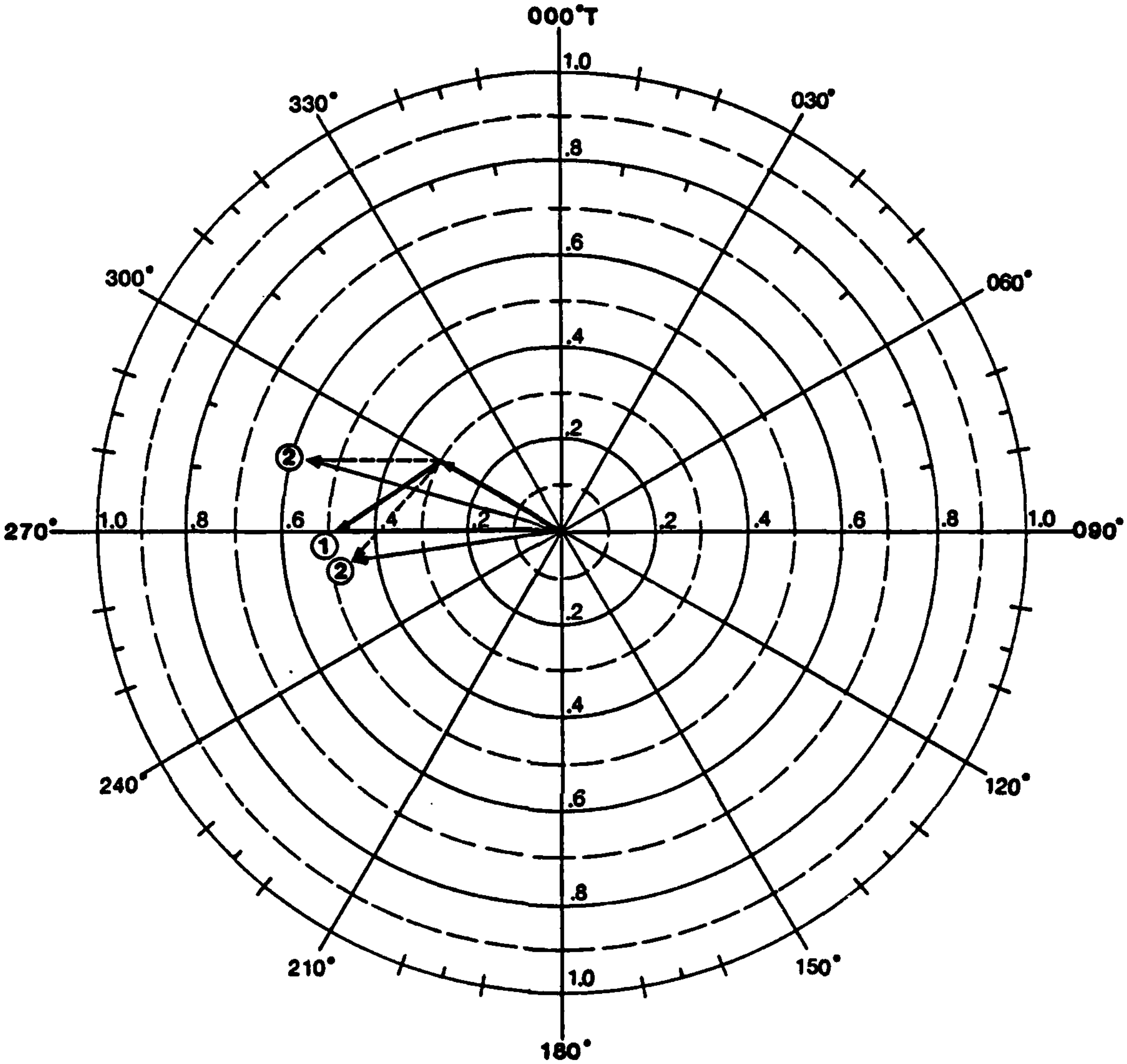
9) LENGTH OF PACK ICE CONTAMINATED (NM) 5

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) West 6./ nm/day

SPILL BEHAVIOR WORK SHEET #7

PLOT OF SPILL DRIFT

SCENARIO 4



SCENARIO 4

1. Principal spill drift vector 270°T/0.5 kts

2. Range of spill drift vectors 262°T/0.45 kts to 285°T/0.55 kts

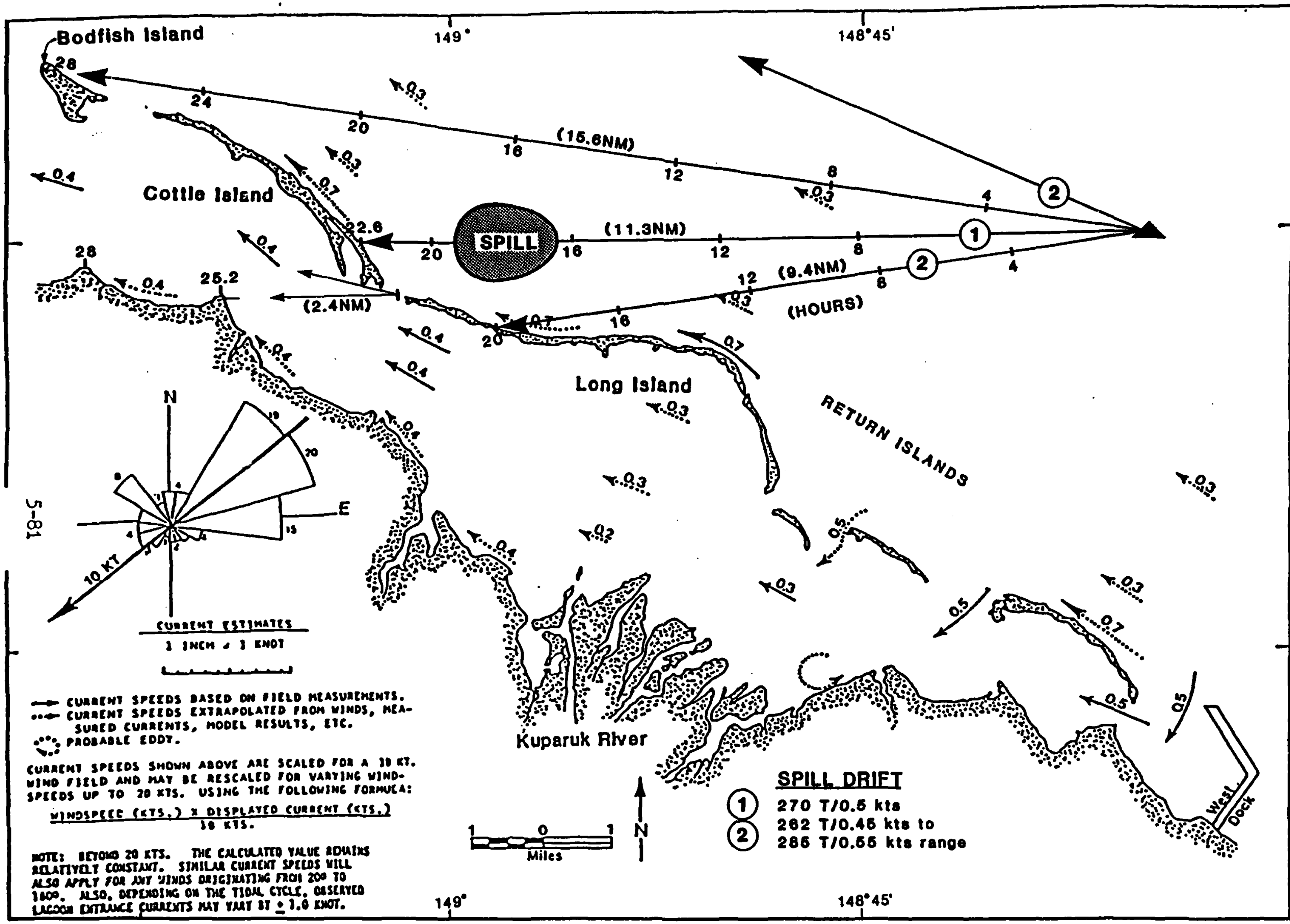


FIGURE 5.4.11 PLOT OF BLOWOUT SPILL DRIFT, WITH IGNITION

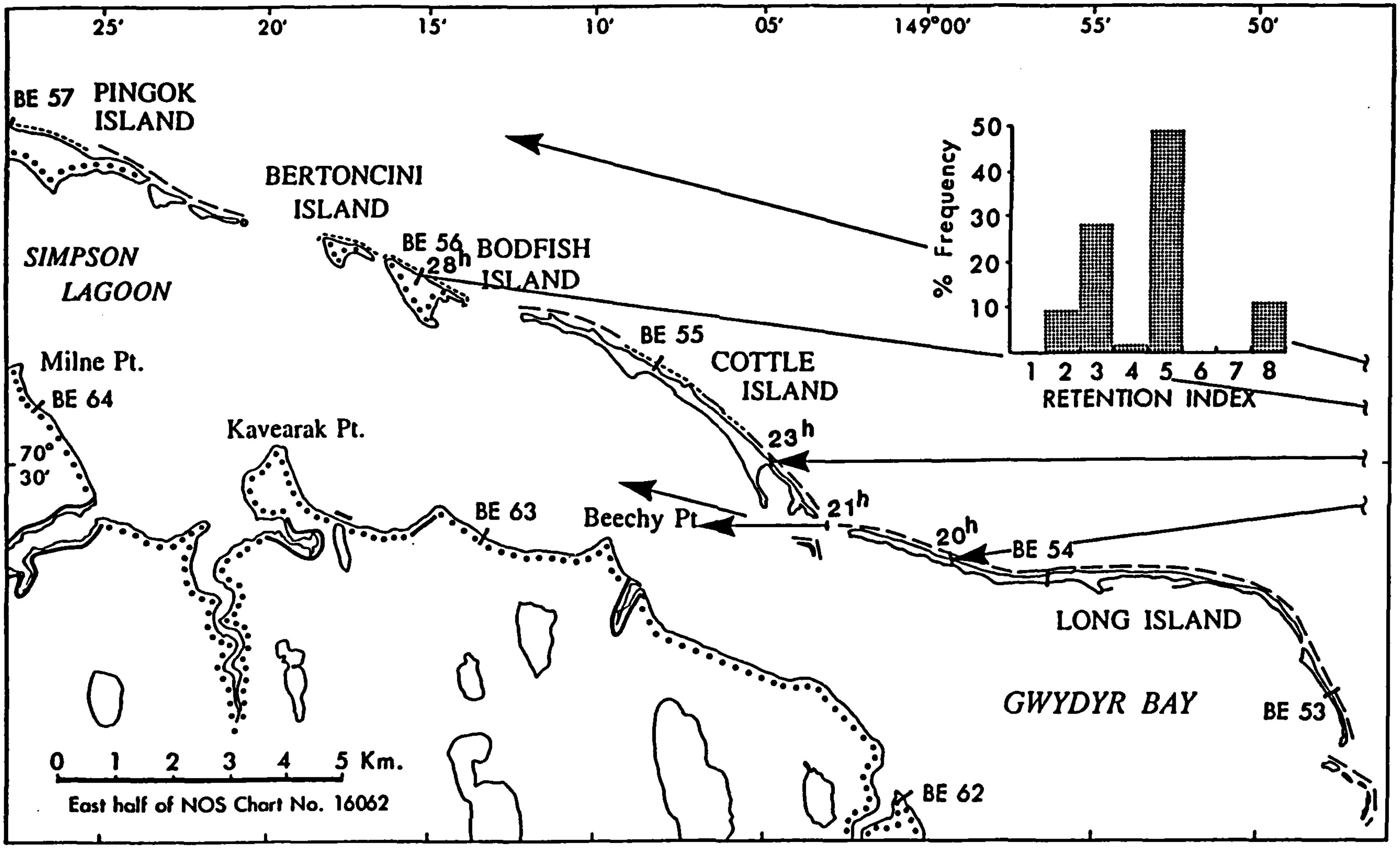


FIGURE 5.4.12 SPILL IMPACT, BLOWOUT WITH IGNITION

5.4.5 SCENARIO 5 - Blowout Under Ice

About noon on 15 March a well being drilled through the fast ice blows out of control.

Spill Location: The spill occurs in the fast ice at 71-10N, 154-10W a little more than 12 miles northeast of Cape Simpson. Figure 5.4.13 shows the location of the spill.

Season: Fast ice, during the middle of March.

Spill Description: This scenario will simply describe the effects of oil and gas under ice without identifying a specific drilling or production situation. That is, we will not specify that the operating unit on the surface is a drill ship, a semi-submersible rig, or a fixed structure. The objective of the scenario is to describe what happens when oil is trapped under fast ice and illustrate the spill storage capacity of the under-ice topography. The information developed in this scenario could be used any time oil or oil and gas are rising from the sea floor.

At about 1200 local time a well being drilled through the fast ice blows out of control. Initial efforts by the drilling crew to control the well are unsuccessful and the resulting blowout is estimated at 10,000 barrels of oil per day. At first only small quantities of oil and gas escape through the drill hole, but the pressure of large quantities of oil and gas trapped under ice finally breaches a crack in the ice over the blowout. This ice failure, together with some melting caused by the temperature of the oil, finally creates an open pool directly above the blowout site. This pool has a radius of about 28 m (Figure 3.6.2), and a vertical side equal to the freeboard of the ice, which is about 18 cm. The oil fills this hole and some pours over the top into the adjacent ice rubble and snow. As soon as the open hole fills with oil, the oil rising from the blowout begins to spread out under the ice where it is contained in the under ice topography. The oil is expected to spread under ice to a radius of almost 700 m from the center of the blowout pool.

Development of Work Sheet Entries

These Work Sheets are not all in numerical order because of the order in which the events occur.

Work Sheet #1: Initial Conditions

This spill of 10,000 barrels of crude per day continues for a period of 30 days before the well can be controlled. In this scenario the well is not ignited intentionally and it does not ignite accidentally during the entire period of the spill.

Initial Conditions

Items 1 through 5 are standard oil properties obtained from the producing company. Since slick thicknesses vary considerably, they are described individually in the oil spill budget. Combustibility would be excellent in large accumulations of oil. The pool of oil above the blowout could be ignited and it is likely that this fire would consume a large percentage of the spilled oil. Burning would probably reduce the amount of oil spreading under the ice. Although there is a large amount of energy in the rising gas bubbles, emulsions are not expected to form (Section 3.6.1).

Environmental Conditions

Item 9 shows that at the time of the blowout the prevailing winds are northeast at 7 to 11 knots. There will be no spill drift until

break-up, therefore the winds in August are also shown on Work Sheet 1. In August the prevailing winds are from the east at 11 knots with a secondary direction from the northeast at 6 knots. At other times the winds are less than 4 knots and may come from any other direction.

The air temperature, item 10, has an average value for March of -27°C. This will significantly chill the escaping oil. The water temperature under the ice is probably close to -2°C, and although the ice temperature is not known, it is probably around -20°C. The wave height, tide, and storm surge data are not significant for this season. Reference (1) shows that in open water the surface currents are 315°T at 0.3 kts. Under ice currents are not known, but they are likely to be lower.

Ice conditions (item 18) describe the heavy fast ice that is in place in late winter. The fast ice is likely to be abot 1.8 m thick and marked by pressure ridges about 1.3 m high. In this area the pressure ridges are not as high as others may be farther from shore. Pressure ridges in this area have been observed to have a frequency of about 17 per nautical mile which is about 9.2 per km (2). Based on this information, there could be 6.4 pressure ridges in a distance of 694 m from the center of the blowout.

There is precipitation in the form of snow about 3% of the time. Fog occurs about 6% of the time, and visibility is expected to be 5 to 10 miles 36% of the time and greater than 10 miles 34% of the time. Figure 5.3.1 shows that there are 11 hours of daylight and 3 hours of twilight.

Work Sheet #2: Physical Properties After Weathering

Because this is a long term spill, physical properties are shown only for the 10 day increment and the thickest oil accumulation recorded in the physical properties charts.

Figure 2.1.4 shows that at low temperatures and in 10 to 15 kts of wind about 12.5% of the oil will evaporate in 10 days. The evaporation curves become very flat at this point indicating that evaporation will be very slow for the period after the initial 10 days. Only the oil accumulating in the hole in the ice above the blowout is exposed to evaporation.

Figure 2.2.4 shows that in 10 days at -20°C viscosity will rise to 30,000 cps. This means that the oil is in the semisolid range. The pour point will be +12°C, which also indicates a highly viscous oil. The density of the oil is also quite high. This will not be important until the oil enters the water at a later date.

Work Sheet #3: Oil Spill Budget

Because of the complexity of the distribution of the oil during the blowout, a diagram will be used for this scenario instead of the tabular format used in the other scenarios.

Work Sheet 3 shows the expected distribution of oil under ice. The blowout is expected to deveop a small circle of open water above the rising oil soon after the release begins. From Figure 3.6.2 it is estimated that the radius of the ring will be about 28 m. The oil is also expected to spread out into the ice rubble and snow adjacent to the ring as shown in Figure 3.6.3; however, once the ring is filled with oil, the large volumes that continue to be released will spread out under the ice. Based on field surveys of under ice topography, (summarized in Table 3.1, Section 3), it is estimated

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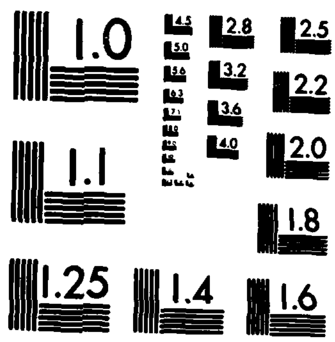

1.0
4.5
5.0
5.6
6.3
7.1
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

that the oil under ice will spread out to a radius of 694 m. If this were a uniform layer of oil, it would have a thickness of about 3 cm. The under ice topography, however, is not likely to be smooth, so most of the oil will be stored in deep cavities in the ice. The capacity of these cavities is significant. It is estimated that the oil that is not contained in the pool above the blowout, which is 295,200 barrels of crude, can be stored in a radius of less than 700 m. This is probably the outer limit of the oil spreading under ice because there may be as many as 6 pressure ridges with keel depths down to 5 or 6 m between the center of the accumulation and the 700 m radius. These deep ice features would provide cavities for storing extremely large volumes of oil.

Work Sheet #4: Spill Volume Remaining

This sheet shows a plot of the volume of oil remaining over a period of 30 days. Most of the spill will spread out under the ice. An opening in the ice is expected to form soon after the spill begins. This opening is expected to have a radius of about 28 m, and with an ice freeboard of a little more than 18 cm, this area would hold a constant volume of about 3,000 barrels. There would also be some evaporation from the wave ring, but because the exposed area is quite small, only about 1800 bbl are expected to evaporate in 30 days. There will be almost no loss from evaporation for the oil under the ice.

Work Sheet #5: Evaporation Rate

Because a new surface of oil is continually being exposed in the center ring, the evaporation pattern is different from the case in which oil has an exposed surface that begins to evaporate at a rapid rate then slows as the oil weathers. In this case the evaporation is assumed to be 2% per day for 30 days, but only for the 3,000 barrels exposed to the atmosphere in the center of the ring. It is estimated that 1,800 bbl evaporate in 30 days. A plot on Work Sheet 5 is not shown for this scenario because evaporation is minimal.

Work Sheet #9: Spreading Under Ice

1) As soon as the oil fills the open water area above the blowout, the oil will begin to move out under the ice following little channels it will form in the under-ice surface. (Section 3.4.1 and Figure 3.4.1). The oil will move in the direction of the under ice current, but once the oil is pooled in a cavity and an equilibrium is achieved, the current will not be strong enough to continue to move the oil.

2) The under-ice topography follows the patterns of snow accumulations on the surface. Snow is an insulator, and therefore cavities under-ice are located below snow drifts. (Section 3.4.2) Typically the variation in under-ice topography is about 20% of the ice thickness. In this case the result would be cavities 36 cm deep.

3) Field surveys show that fast ice offshore on the North Slope has an average storage capacity of about 31,000 m^3/km^2. Based on these surveys, the 295,200 bbl that are expected to move under the ice could be contained in an area with a radius of less than 700 m.

4) The area selected for this scenario has a relatively high frequency of pressure ridges. Based on the expected frequency of pressure ridges in the area, there could be 6.4 pressure ridges between the center of the blowout and the outer edge of the oiled area. Assuming a height to depth ratio of 1 to 4 or 5, these pressure ridges may have keels that

extend 5 to 6 meters below the surface. This would provide a very large area to store oil. The oil could also move up into unconsolidated pressure ridges, and could also rise to the surface through cracks in the ice in or adjacent to the ridges.

Overall, the under-ice topography has tremendous capacity to store oil. This has the effect of limiting the area of the spill, which is good. This also provides some opportunities for spill recovery by drilling down to the areas where the oil is pooled under the ice. If the blowout stops by the middle of April, the oil stored under ice will remain stable for a few weeks. But in a short time melting will begin and the oil will begin to migrate to the surface. This will mark the beginning of the break-up spill situation.

Work Sheet #11: VerticalMigration of Oil Through Ice

1) In March and April the brine channel network will develop to permit the oil to move slowly up through the ice. Brine channels will grow vertically from their original position near the oil lens to about 10 to 15 cm from the surface of the ice. They will also increase in size to about 4 mm and become connected with small feeder channels (Section 3.7.2). As melting continues, the oil will have a path all the way to the surface.

2) Oil begins upward movement in the ice as soon as the brine channels develop, but the movement is not always continuous. The vertical migration may be stopped periodically by fresh water from the surface running down in to the brine channels and freezing. The oil may also be trapped periodically as it becomes more viscous in colder temperatures. Figure 3.7.2 shows that at a relatively slow rate the oil may surface in 6.5 weeks and at a fast rate it may surface in 2.5 weeks. Figure 3.7.3 shows that regardless of when the vertical migration begins, all of the oil surfaces quickly when break-up begins.

3) Once melt pools form in the depressions in the snow, oil begins to float on the surface. The increased amount of energy that is absorbed by the oil leads to a rapid growth in the area and the depth of the pools. Oil on the melt pools may be from 1 to 10 mm thick. After the ice melts through to the sea surface, high energy vortices will flush the water and oil down through the ice. This action may be cyclic with the tides and will increase the size of the melt holes. Once the oil is on the surface of the ice, it will also quickly be released to the sea by flowing off the sides of the ice or simply being released in mass during break-up.

Work Sheet #6: Spreading on Open Water

The under-ice blowout is essentially a "safe" spill as long as the oil remains in the ice. At break-up the oil will begin to move and then the spill will become an environmental threat. Work Sheet 6 provides an estimate of the threat potential when the spill begins to move.

1) The radius of the spill when it is under ice is quite small because of the carrying capacity of the under ice topography. After the oil migrates to the surface and pools on the ice there is an opportunity for the spill area to become much larger. As the ice melts the oil will stream off, and as the oil fills cracks in the ice and leads, it will have an opportunity to move in almost any direction. In some cases the oil may be carried away with the drifting ice and not released until it is many miles from the spill site. Although the spill radius begins at less than 700 m, it is likely to become much larger at break-up.

2) Slick thickness would be very difficult to define in this case. The oil that is trapped under-ice may be in the form of particulates up to accumulations in lenses that are several centimeters thick and one or more meters across. After the oil migrates up through the ice and is released into the water, there are many opportunities for additional divisions to occur. The resulting spill configuration is likely to include clusters and patches of oil containing particles of millimeter size up to clumps that are tens of centimeters across and several centimeters thick. The sea water is very cold at this time, probably around $-2^{o}C$. The oil that has been trapped under the ice has hardly weathered, but it will weather very quickly as soon as it is exposed to the air. Because of the low temperatures and weathering, the oil will have a very high viscosity, in the semi-solid range, and a pour point of 5 to $10^{o}C$. The spill products will therefore be dense and highly viscous.

3) Work Sheet 7 shows the plot of the spill drift vector. The primary drift vector is $290^{o}T$ at 0.58 knots and a secondary drift vector is $285^{o}T$ at 0.34 knots. Figure 5.4.14 shows a geographic plot of the spill drift. The closest point of land to the spill is the area of Cape Simpson, but if the spill moves in the direction of the prevailing winds and currents, it will not reach land quickly, because it will move toward Barrow rather than Cape Simpson. Using the most likely course and speed, the spill would arrive at the barrier islands southeast of Barrow more than four days after the oil is released.

4) The closest land is about 12 miles away and the most distant point of contact is about 37 miles away. North winds could drive the spill ashore at Cape Simpson in about 21 hours.

5) The time of arrival of the spill at the shoreline depends on the time of break-up.

6) There is a considerable potential for spill impact at Barrow if the slick moves with the prevailing winds and currents. The possible areas and type of impact are described on Work Sheet 6 and illustrated on Figure 5.4.15.

The most likely first point of contact of the spill would be the non-vegetated barrier islands that form Elson Lagoon. The potential for damage here is not large and the oil is likely to be removed by wave action and ice within a year. But if there is a large deposit of oil on the shore line, it would be a source of pollution to fish and animals in the offshore areas. Because of this problem, a clean-up effort on the barrier islands should be considered.

If the oil should enter Elson Lagoon, and this seems likely if the drift transports the spill to Barrow, there is a much greater potential for damage. Here there are 19 miles of shoreline that consist of lagoon-facing mainland shore, peat shore, and sheltered tidal flats. The potential for environmental impact is large for each shoreline type and in each case the residence time of the oil is likely to be a matter of years if the oil is not removed. If large amounts of oil remain on the shoreline at break-up, the result could indeed be devastating. The spill response effort should therefore be directed to protecting the lagoon entrance from the oil. If the oil can be collected at the entrance to Elson Lagoon, the damage would be minimal.

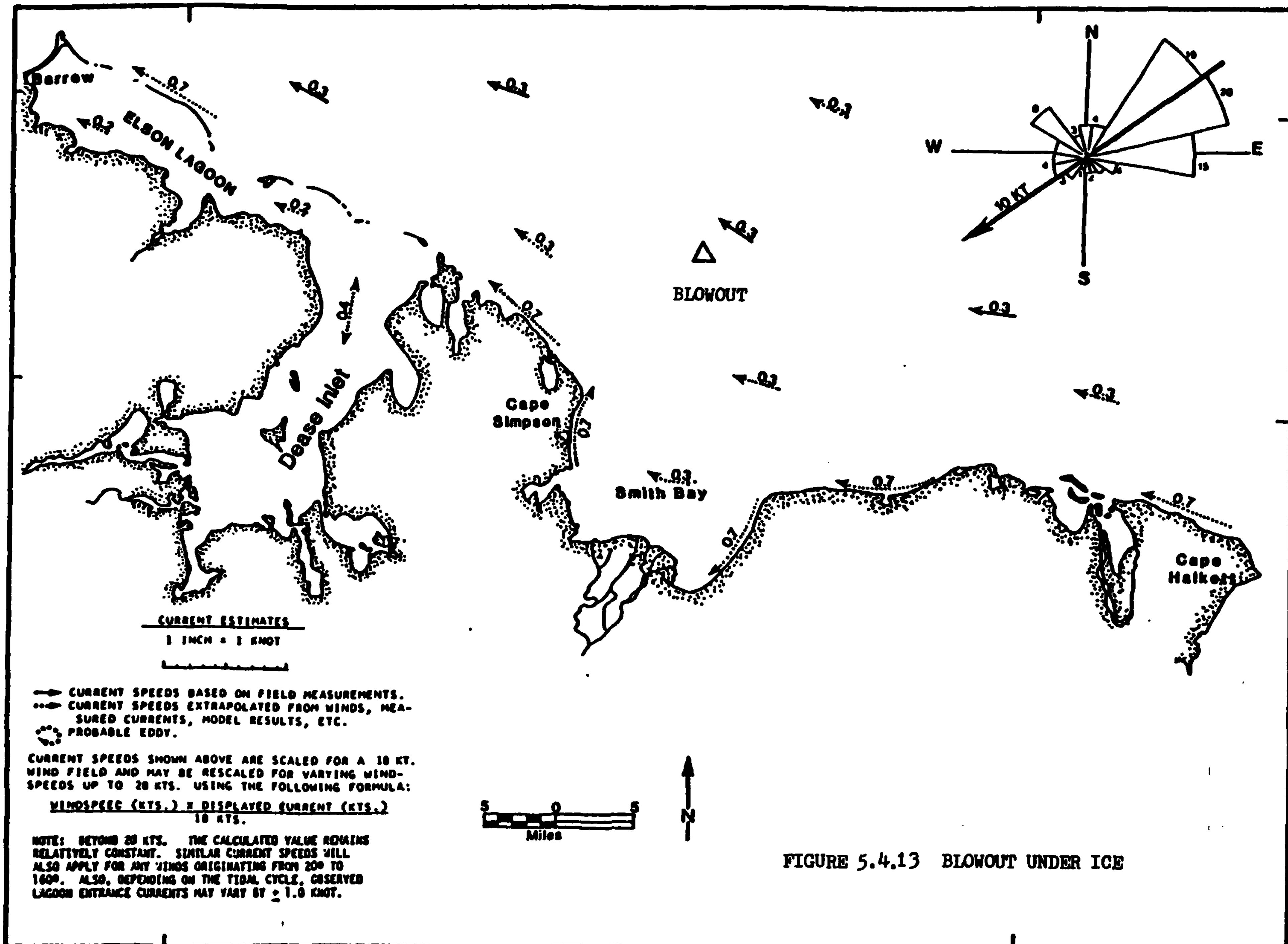


FIGURE 5.4.13 BLOWOUT UNDER ICE

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 5

DATE AND TIME SPILL BEGAN 1200 15 March

SPILL LOCATION Cape Simpson 71-10N 154-10W TYPE OIL North Slope Crude

AMOUNT SPILLED 10,000 bbl/day for 30 days--300,000 bbl

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) 60°C (well head) 2) SP. GRAVITY (g/cc) 0.895

3) VISCOSITY (cp) 35.0 4) POUR POINT (°C) -9.4°C 5) SOLUBILITY 29.2g/m^3

6) SLICK THICKNESS (1) see Work Sheet 9 (3)
(2) spreading under ice (4)

7) COMBUSTIBILITY Excellent in wave ring above blowout

8) EMULSIFICATION emulsions not expected

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) NE, 7 to 11 kts March , E 11 kts 30%; NE 6 18%; <4 kts remainder, equally likely from any direction, August

10) TEMPERATURE (°C): AIR -27 11) WATER -2°C 12) ICE -20°C

13) WATER DEPTH (m) 18 m 14) WAVE HEIGHT (m) --- 15) CURRENTS 315°T/0.3 Kts (surface)

16) TIDE (m) --- 17) STORM SURGE HEIGHT ABOVE MSL (m) ---

18) ICE CONDITIONS Fast ice 1.8 m (6 ft) thick; pressure ridges 1.3 m high (4.3 ft), frequency of 17/NM or 9.2/km. Estimate 6.4 pressure ridges in a distance of 694 m from center of blowout.

19) PRECIPITATION Precip as snow 3% of the time

20) VISIBILITY Fog 6% of time Vis 5 to 36%; 10 34% 21) DAYLIGHT (HRS) 11, twilight 3

SPILL BEHAVIOR WORK SHEET #2
SCENARIO 5

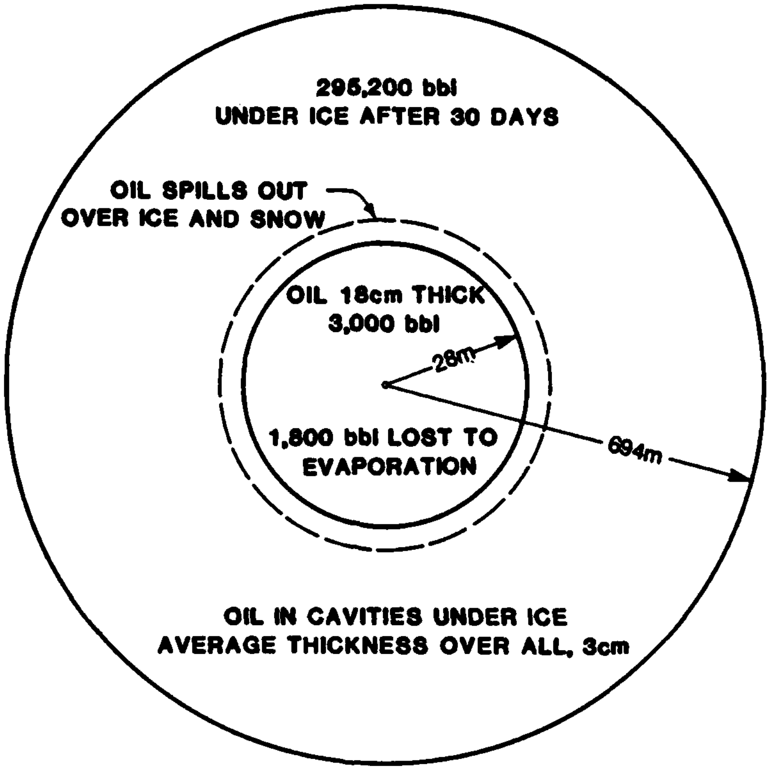
PHYSICAL PROPERTIES AFTER WEATHERING

1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)											87.5	
4) VISCOSITY (cps)											30,000	
5) POUR POINT (°C)											+12	
6) DENSITY (g/cc)											0.94	
7) SOLUBILITY (g/m3)											2	

REMARKS:

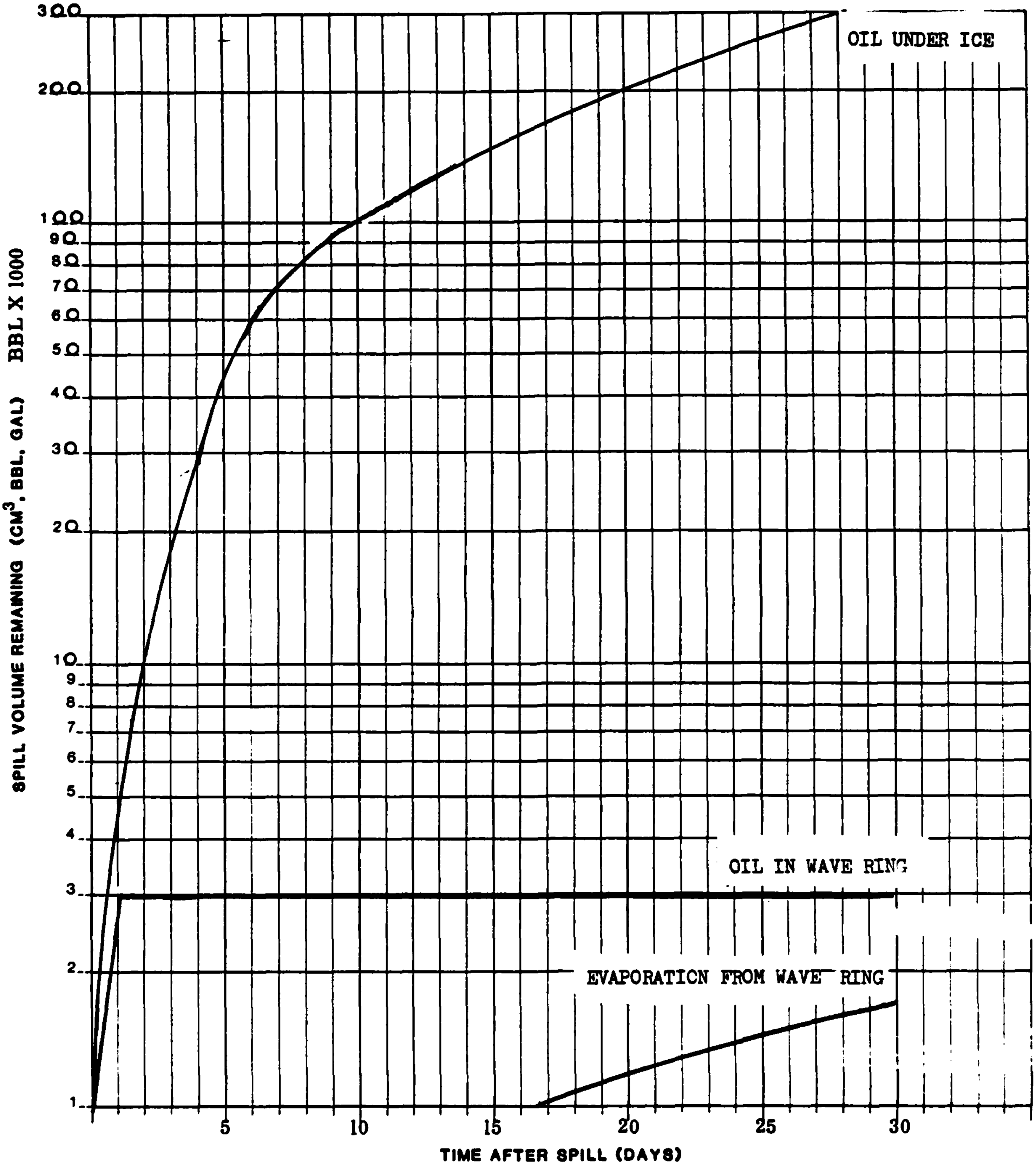
WORK SHEET #3

SCENARIO 5 BLOWOUT UNDER ICE



SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING



SPILL BEHAVIOR WORK SHEET #9
SPREADING UNDER ICE

1) MOVEMENT UNDER FAST ICE As the accumulation of oil grows under ice, oil will move out in rivulets as shown in Figure 3.4.1. This movement will continue until an equilibrium is established. Current will not be a factor in moving the oil under-ice since even the normal surface current velocity (0.3 kts) is less than the threshold velocity of 0.4 kts (Section 3.4.5). 95% of the oil will collect in cavities under ice.

2) UNDER ICE TOPOGRAPHY Normal variation expected to be about 20% of the ice thickness, in this case about 36 cm. In areas where the under-ice is flat the oil would achieve an equilibrium thickness of about 8 mm. Under-ice cavities line up with, and occur under, surface snow patterns (Section 3.4.2).

3) UNDER ICE STORAGE CAPACITY Average under-ice storage capacity in this area 31,000 m^3/km^2. The 295,200 bb. released under the ice in this spill could be contained in an area with a radius of 694 m. If it were evenly distributed in this area it would have a thickness of 3 cm.

4) LARGE UNDER ICE FEATURES This area could have 6.4 pressure ridges between the center of the blowout and the outer edge of the under ice oil. Since the height to depth ratio of pressure ridges is 1 to 4 or 5, these ridges could have keels that extend to a depth of 5 to 6.5 m (Section 1.2). This could provide a very large storage capacity in some areas. Oil may also become incorporated in unconsolidated ridges or may even rise to the surface through cracks in the ice or adjacent to ridges.

SPILL BEHAVIOR WORK SHEET #11
VERTICAL MIGRATION OF OIL THROUGH ICE

1) BEGINNING OF MIGRATION In March and April the brine channel network develops to permit the oil to move slowly up through the ice. Brine channels grow from the oil lens to about 10 to 15 cm from the surface of the ice. The brine channels also increase in size to about 4 mm and become connected with small feeder channels (Section 3.7.2). As melting continues, the oil will have a path to the surface.

2) RATE OF MIGRATION Oil moves upward in the ice early, but the movement is not always continuous. The vertical migration is stopped by fresh water from the surface running down into the brine channels and freezing. The oil may also be trapped periodically as it becomes more viscous in colder temperatures. The oil may surface in 6.5 weeks at a slow rate and in 2.5 weeks at a fast rate. Regardless of when the vertical migration begins, all of the oil surfaces quickly at breakup (Figure 3.7.3).

3) BEHAVIOR ON SURFACE Once melt pools form in the depressions in the snow, oil begins to float on the surface. The increased amount of energy that is absorbed by the oil leads to a rapid growth in the area and the depth of the pools. Oil on the melt pools may be from 1 to 10 mm thick. As the melt holes increase in size, high energy vortices will flush the water and oil down through the ice. This action may be cyclic with the tides and will increase the size of the melt holes. Once the oil is on the surface of the ice, it will quickly be released to the sea by flowing off the sides of the ice or simply being released in mass during break-up.

SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER

		THICK SLICK	THIN SLICK
1)	SPILL RADIUS (m):	700 m	---

2) SLICK THICKNESS (mm): Variable. Particulate to several cm.

3) SPILL DRIFT VECTOR: AVERAGE 290°T/0.58 kts RANGE 285°T/0.34 kts to 290°T/0.58 kts

4) DISTANCE TO SHORELINE (NM): MAX 37 MIN 12

TIME TO REACH SHORELINE (HRS): MAX 4.5 days MIN 21 hours

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST --- LATEST --- Depends on breakup

6) LENGTH OF SHORELINE CONTAMINATED (NM): ____

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	8.9
2		6	3.1
3	4.4	7	7.1
4		8	

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- o SHORELINE TYPE 3) Non-veg. barrier island. 5) Lagoon-facing mainland shore. 6) Peat shore. 7) Sheltered tidal flats
- o IMPACT 3) Minimal, but could be transported offshore. 5) low, but may enter other areas. 6) serious effect on nutrient chain. 7) absorbed in organic debris
- o PERSISTENCE 3) <1 year. 5) years. 6) years. 7) years
- o PROTECTION 3) offshore boom, but probably could be left exposed, 5) to 7) Boom off lagoon entrance
- o CLEAN-UP 3) small amount of oil could be left in place; remove large accumulation. 5) Clean to protect tundra margin. 6) Remove peat, 7) Clean tidal flats manually

7) DISTANCE TO PACK ICE (NM): 20 TIME TO REACH PACK ICE(HRS) MAX 4 days MIN 1 day

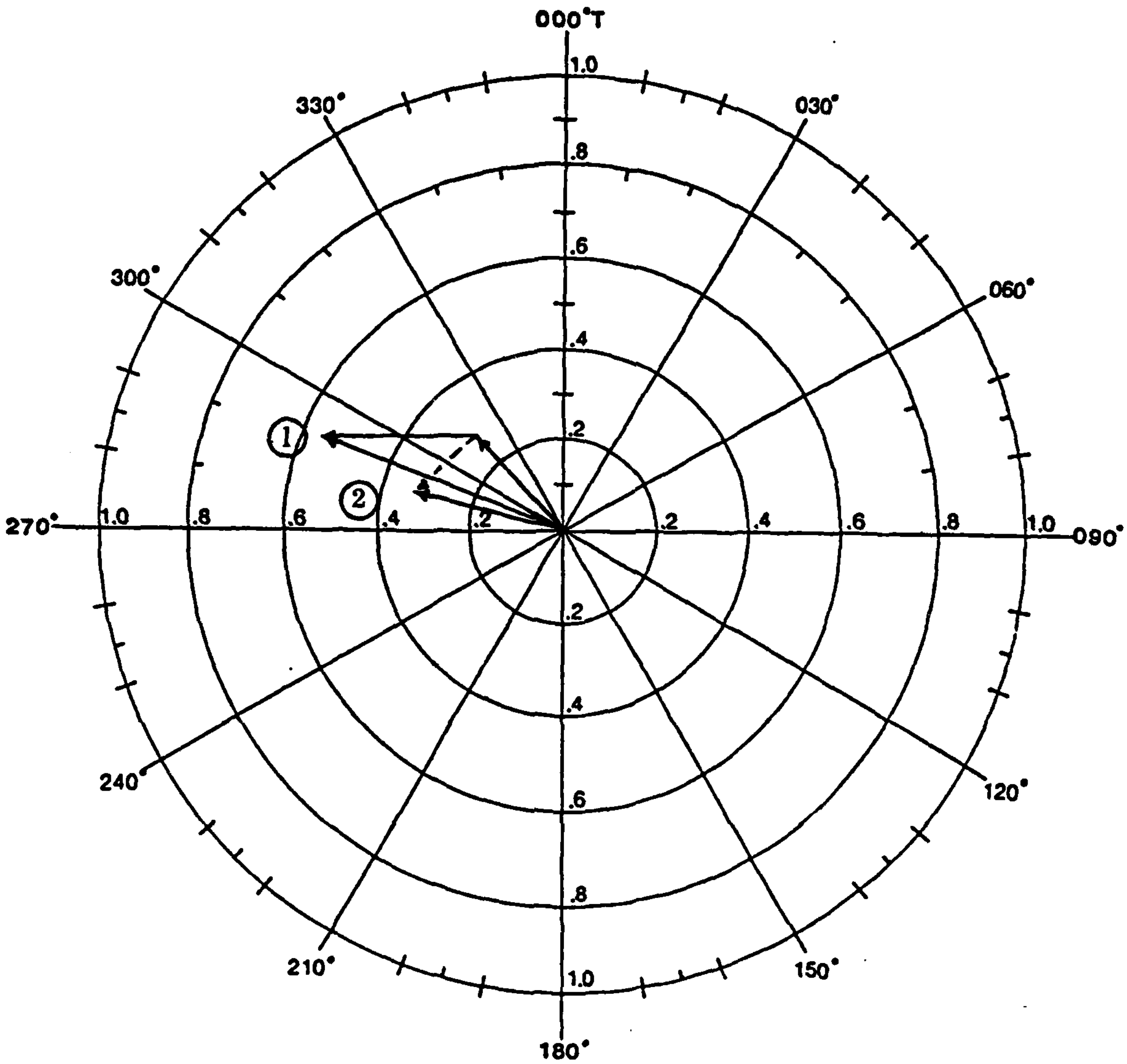
8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST --- LATEST ---

9) LENGTH OF PACK ICE CONTAMINATED (NM) Indef.

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) 6

SPILL BEHAVIOR WORK SHEET #7

PLOT OF SPILL DRIFT



SCENARIO 5

1. Primary drift vector 290°T/0.58 kts

2. Secondary drift 285°T/0.34 kts

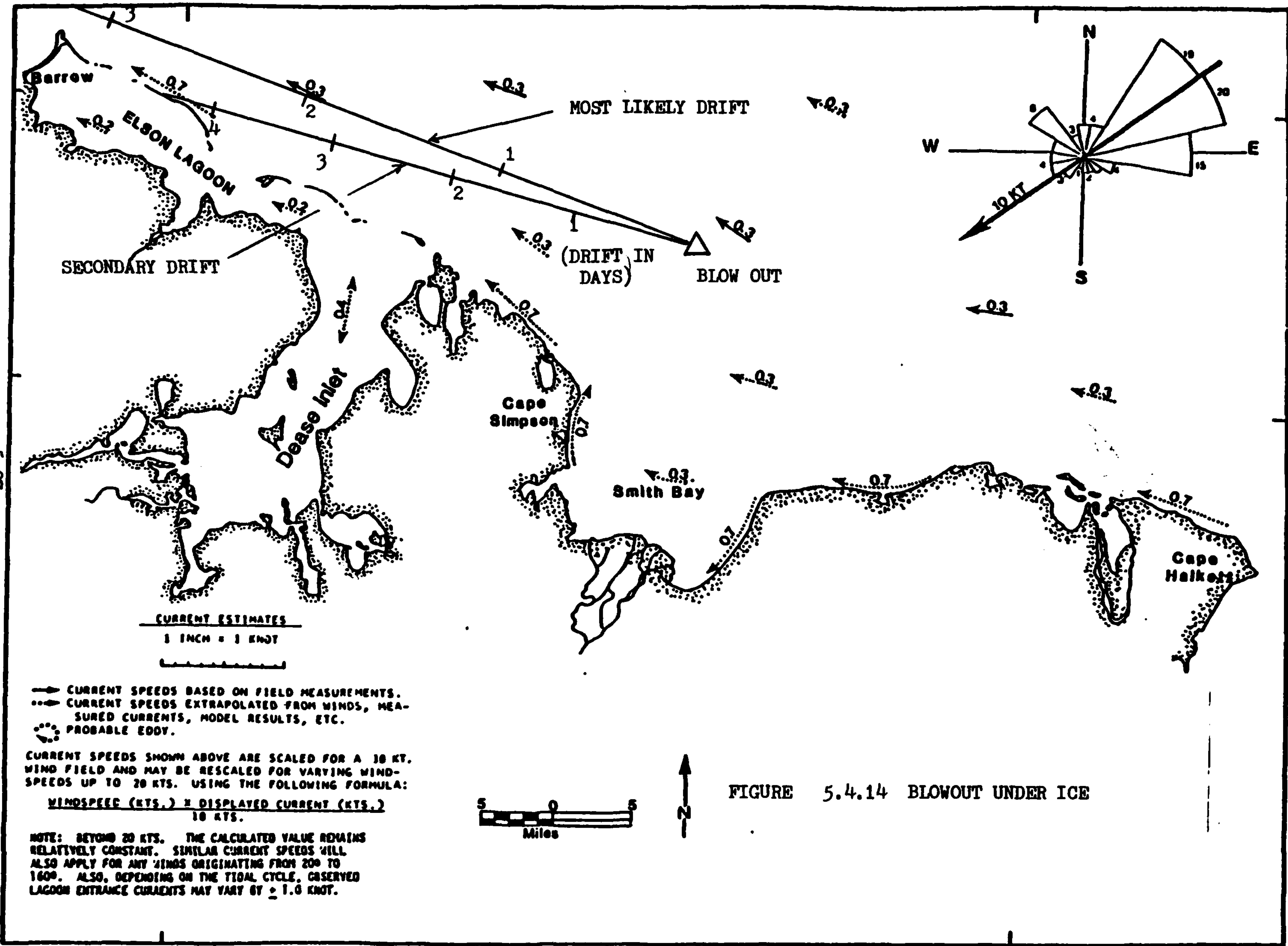


FIGURE 5.4.14 BLOWOUT UNDER ICE

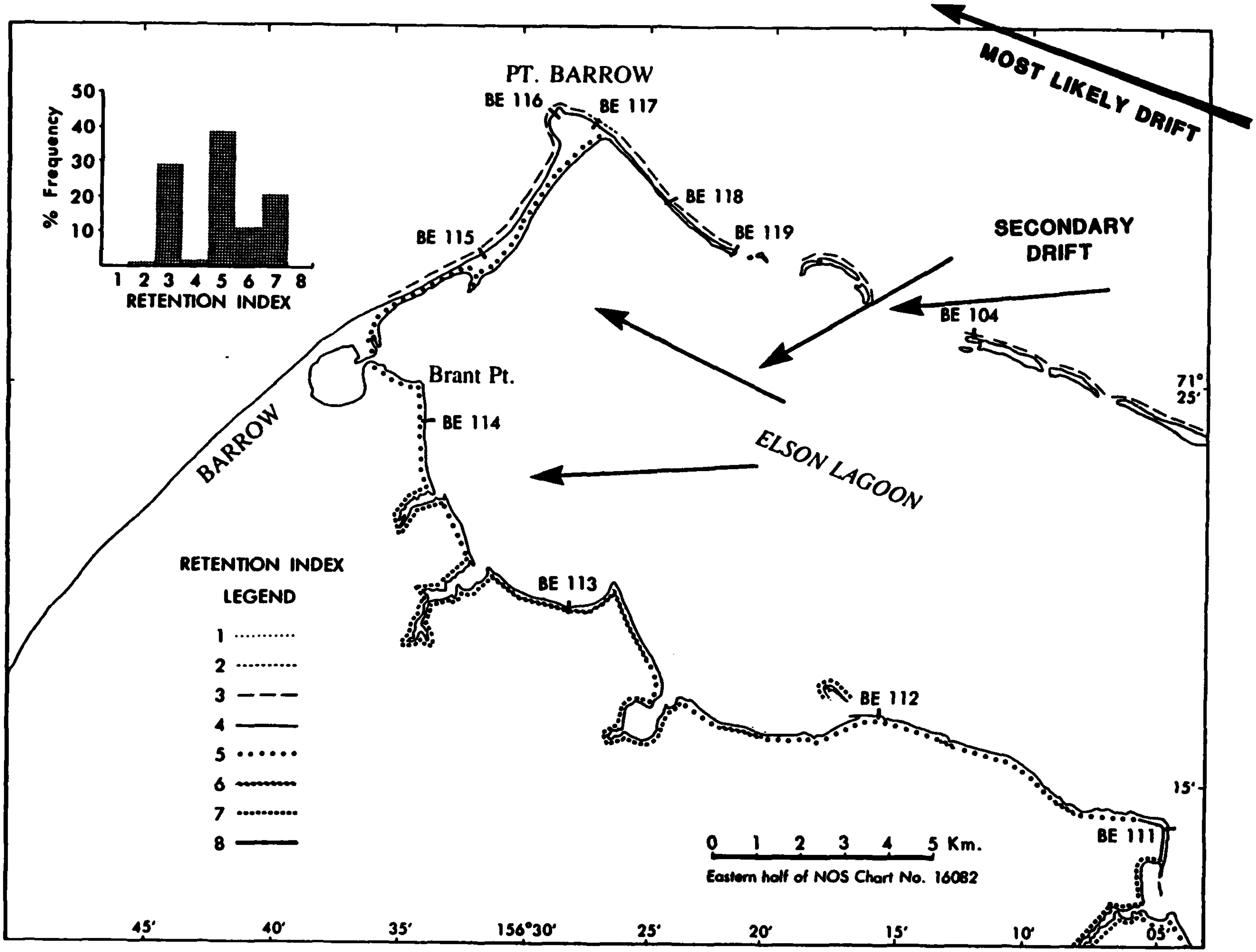


FIGURE 5.4.15 BLOWOUT UNDER ICE

5.4.6 SCENARIO 6 - Tanker Spill

At about noon of 1 August a tanker collides with a supporting icebreaker and spills oil from two tanks through a gash in the starboard side of the ship.

Spill Location: The spill occurs at 71-30N, 154-20W, about 28 miles northeast of Cape Simpson. Figure 5.4.16 shows the location of the spill.

Season: Break-up during the first week in August.

Spill Description: A tanker is proceeding westward in the Beaufort Sea through water containing some heavy ice accumulations. The ice is thick and very soft so that it does not break as a the ice breaking bow of the tanker rides up over it. As a result, extremely high power is needed to penetrate the heavy ice areas, and the tanker is proceeding with the support of an icebreaker. The icebreaker is moving ahead of the tanker pushing smaller floes out of the way and clearing a path through the heavier accumulations of ice. The ice breaker had been making about 6 to 8 knots when it ran up on the remains of a thick pressure ridge and suddenly became dead in the water within a distance of less than 50 meters. The tanker backed down full and swerved to avoid the ice breaker, but there was not enough room to stop. The tanker collided with the stern of the ice breaker and tore a gash 6 m long through her double hull above the water line exposing two tanks filled with North Slope crude.

The oil immediately began spilling out on the porous ice and into an open water area farther aft along the hull. (The icebreaker maneuvered to clear the area because of the fire hazard.) Some of the oil spread out on the pools of water on the ice, but most of it was released directly into the water. Because of the change in albedo and the heating of the sun, the oil that had originally been deposited on the ice soon streamed off the soft ice and was also deposited in the water.

Efforts to transfer oil from the ruptured tanks were only partially successful, and the release of oil finally stopped when the tanks had emptied to the level of the gash in the hull. At that time about 100,000 bbl of crude had spilled into the water.

Development of Work Sheet Entries

These Work Sheets are not all in numerical order because of the order in which the events occur.

Work Sheet #1: Initial Conditions

Items 1 through 5 are standard oil properties obtained from the ship's records. The oil temperature is assumed to be the same as the average ambient air temperature, although it could be somewhat cooler because of the tanks riding in the water. In this example the specific gravity, viscosity, and solubility have not been corrected for this initial temperature.

6) The slick thickness is in the range of 5 to 8 mm in most areas but some larger accumulations have a thickness of 10 to 20 mm.

7) Combustibility would be excellent in accumulations of 5 mm and greater. Precautions are taken not to ignite the oil because a fire is likely to endanger the ship.

8) There is some possibility that emulsification could occur, but wave energy is likely to be low because of the ice cover. As a result, emulsification is not likely.

9) The prevailing wind is from the east at 10 kts with a lower frequency of winds from both east and west at 5 kts.

10), 11), and 12) The air, water and ice temperatures are all quite close together. The oil is probably near 0°C when it is spilled and will take on the temperature of the water quickly.

14) Wave height is expected to be less than 1 meter and not significant to this problem.

15), 16), and 17) The current is westerly at 0.3 kts. The tide will not be significant in the offshore area. Consider the possible impact of a storm surge only if one is likely to occur based on the criteria provided in reference (1).

18) The ships are moving in deteriorating fast ice. There are many cracks, open leads, and even open water areas. The ice is very soft, but this makes going difficult in the heavy ice areas because the ice doesn't break. Instead, the ships must push through using high power.

19), 20), and 21) Precipitation, visibility, and daylignt are not important factors in this scenario.

<u>Work Sheet #2: Physical Properties After Weathering</u>

Because of the fairly high temperatures and steady winds, the spill has a good opportunity to evaporate. In some areas 20% of the oil will be lost to evaporation.

As the oil weathers in the near 0°C arctic temperatures, the viscosity will increase so that the oil will be in the semi-solid range, although it would be less viscous than in a winter spill. Even during break-up the weathered crude is likely to be thick and viscous.

The high pour point of the various thicknesses of spilled product is another indicator of a highly viscous, immobile product. In every case, the pour point can be expected to be well above the ambient air temperature.

The density of the spilled crude becomes quite high as it weathers, and although the oil may not sink, it could be easily forced under ice accumulations that have a density of about 0.92 g/cc.

Solubility tends to decrease slightly as the oil weathers. The solubility may have some effect on the toxicity of the spill, but it will not cause any important loss of oil.

<u>Work Sheet #3: Oil Spill Budget</u>

The oil spilling from the ship onto ice and into cold water could result in slicks of varying thicknesses depending on how fast it cools and the extent to which its movement is restricted by ice. To illustrate spill behavior for the tanker spill, slick thicknesses have been assumed to be 5 mm, 10 mm, and 20 mm with a distribution of 60%, 20%, and 20% respectively. Since this scenario does not consider a response effort, the only loss of the spill is to evaporation. Work Sheet 3 shows varying evaporation rates for the various spill thicknesses over time. The slick is assumed to cover a constant area, and evaporation would result in a decreasing thickness. Considering all of the slick segments together, a little more than 20% of the spill is lost to evaporation in ten days.

<u>Work Sheet #4: Spill Volume Remaining</u>

Work Sheet 4 shows a plot of spill volume remaining over a ten day period. This Work Sheet could

also be used to plot the results of the spill response effort.

Work Sheet #5: Evaporation Rate

Work Sheet 5 shows a plot of evaporation rate for the three slick thicknesses.

Work Sheet #6: Spreading on Open Water

1) The radius of the slick could range from about 460 m to 870 m depending on the slick thickness or the distribution of the slick thicknesses. Using thicknesses of 5, 10, and 20 mm in the proportions mentioned earlier, the radius would be about 870 m. There would also be a sheen bleeding out from the heavier accumulations of oil.

2) Slick thicknesses are 5, 10, and 20 mm.

3) Work Sheet 7 that follows shows that the principal spill drift vector is 293°T at 0.6 kts and that the range of drift is expected to be between 272°T at 0.4 kts and 325°T at 0.2 kts. Figure 5.4.17 shows a plot of the expected movement. The most likely track of the spill would carry the oil many miles away from land. If the spill takes the track to the northwest, it is likely to coat the pack ice. If it follows a westerly path, it would threaten the barrier islands near Barrow and Elson Lagoon.

4) The closest point of land is Cape Simpson, which is one of the least likely tracks. The farthest point of land is at Barrow, which is a fairly likely point of contact.

5) The time of arrival at the shoreline depends on when the area becomes free of ice so the oil can move with the winds and current.

6) There is a potential for contaminating more than 23 miles of shoreline near Barrow if the spill follows a westerly track. This includes 4 miles or more of barrier island, almost 9 miles of lagoon-facing mainland shore, plus 6 miles of peat shore and 7 miles of tidal flats. Figure 5.4.18 shows the coastal area and the shoreline types.

If the spill does move west, the most likely first point of contact would be the non-vegitated barrier islands that form Elson Lagoon. The potential for damage on the barrier islands is not large and the oil is likely to be removed by wave action and ice within a year. However, as the spill is removed from the barrier islands, it may be transported by currents to other areas where there is a potential for environmental damage. Because of this problem, a clean-up effort on the barrier islands should be considered.

If the oil should enter Elson Lagoon, and this seems likely if the drift transports the spill to Barrow, then there is a much greater potential for damage. Here there are 19 miles of shoreline that consist of lagoon-facing mainland shore, peat shore, and sheltered tidal flats, that all face the threat of heavy oil accumulations. In each case the potential for environmental impact is large and in each case the residence time of the oil is likely to be a matter of years if the oil is not removed.

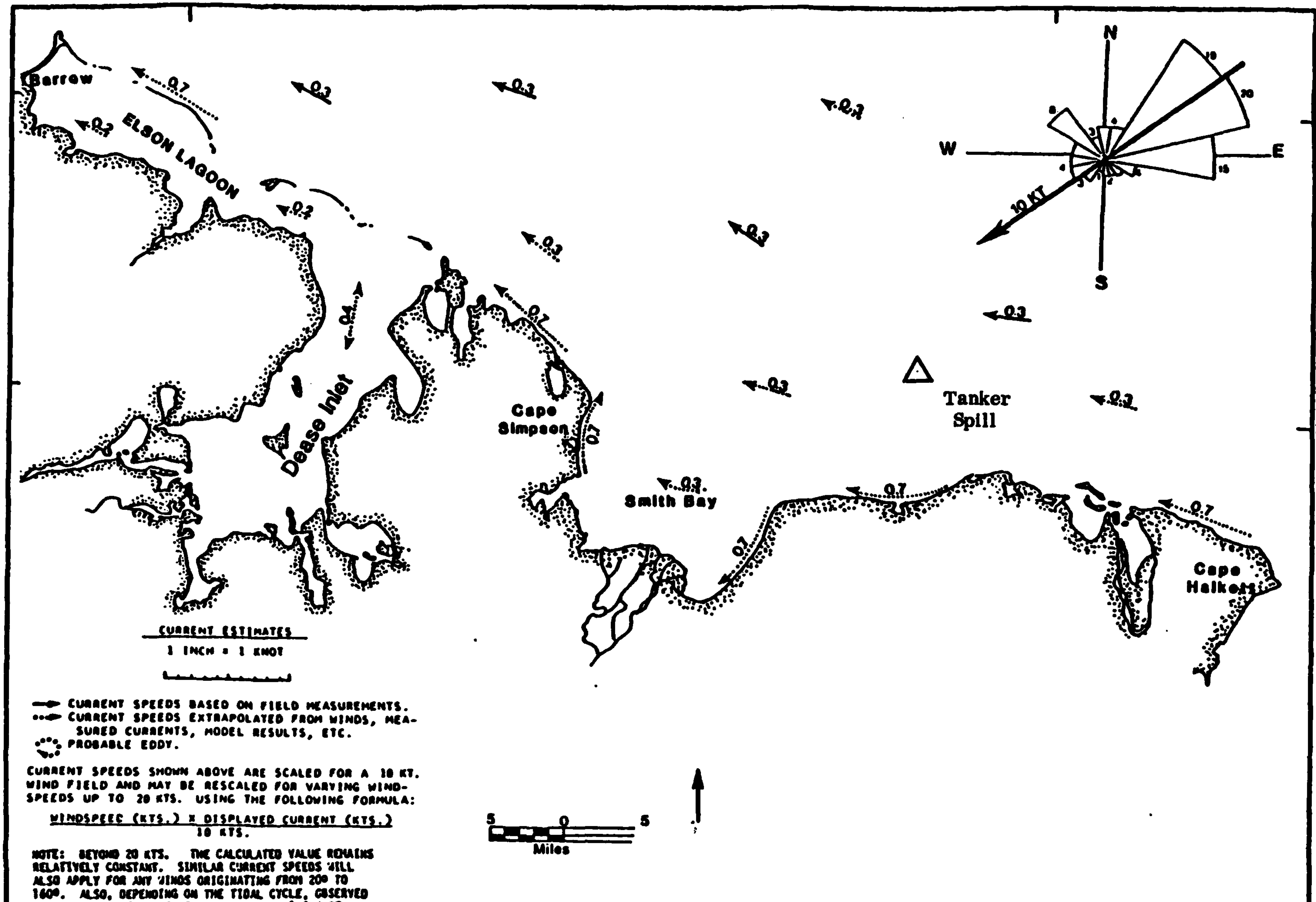


FIGURE 5.4.16 LOCATION OF TANKER SPILL

SPILL BEHAVIOR WORK SHEET #1
INITIAL CONDITIONS
SCENARIO 6

DATE AND TIME SPILL BEGAN 1200 Local 1 August

SPILL LOCATION 71-30N 154-20W TYPE OIL North Slope crude

AMOUNT SPILLED 100,000 bbl

INITIAL OIL CONDITIONS

1) TEMPERATURE (°C) +3 2) SP. GRAVITY (g/cc) 0.89

3) VISCOSITY (cp) 35 4) POUR POINT (°C) -9.4°C 5) SOLUBILITY 3/gm³

6) SLICK THICKNESS (1) 5-8 mm (3) 20 mm
(2) 10 mm (4)

7) COMBUSTIBILITY Excellent in accumulation > 5 mm

8) EMULSIFICATION Could occur in areas of high wave energy, but partial ice cover is likely to keep waves down, therefore emulsification is unlikely

ENVIRONMENTAL CONDITIONS

9) WIND (Direction/Velocity, Kts) NE 5 kts 15%; E 10 kts 28%; W 5 kts 12%

10) TEMPERATURE (°C): AIR +3 11) WATER 0°C 12) ICE 0°C

13) WATER DEPTH (m) 31 m 14) WAVE HEIGHT (m) <1 m 15) CURRENTS 298°T/0.3 kts

16) TIDE (m) 0.3 17) STORM SURGE HEIGHT ABOVE MSL (m) 1 m

18) ICE CONDITIONS Deteriorating fast ice; many cracks, open leads, and open water areas

19) PRECIPITATION Rain 10% of time, snow 6% of time

20) VISIBILITY 5 to 6 miles 21) DAYLIGHT (HRS) 24

SPILL BEHAVIOR WORK SHEET #2
SCENARIO 6

PHYSICAL PROPERTIES AFTER WEATHERING

1) DAY	1				3				10			
2) SLICK	1	2	3	4	1	2	3	4	1	2	3	4
3) EVAPORATION (% Rem.)	84	87	88		82	83	86		77	79	83	
4) VISCOSITY (cps)	2200	2000	1600		4000	3100	2300		6000	4800	3800	
5) POUR POINT (°C)	+5				+8				+12			
6) DENSITY (g/cc)	.935				.94				.95			
7) SOLUBILITY (g/m3)	5				3.3				2			

REMARKS: 1) 5mm, 2) 10 mm, 3) 20 mm.

SPILL BEHAVIOR WORK SHEET #3
OIL SPILL BUDGET
SCENARIO 6

Day 1

Location	Thickness	Area	%Remaining	Volume
SHIP	5 mm	$1.9 \times 10^6 m^2$	84	$8,000 m^3$ (50K bbl)
SHIP	10 mm	$3.18 \times 10^6 m^2$	87	$2,800 m^3$ (18K bbl)
SHIP	20 mm	$1.59 \times 10^5 m^2$	88	$2,800 m^3$ (18K bbl)
			TOTAL	86,000 bbl

Day 3

Location	Thickness	Area	%Remaining	Volume
30 NM DOWNWIND	5 mm	---	82	$7,800 m^3$ (49K bbl)
30 NM DOWNWIND	10 mm	---	83	$2,600 m^3$ (17K bbl)
30 NM DOWNWIND	20 mm	---	86	$2,700 m^3$ (17K bbl)
			TOTAL	83,000 bbl

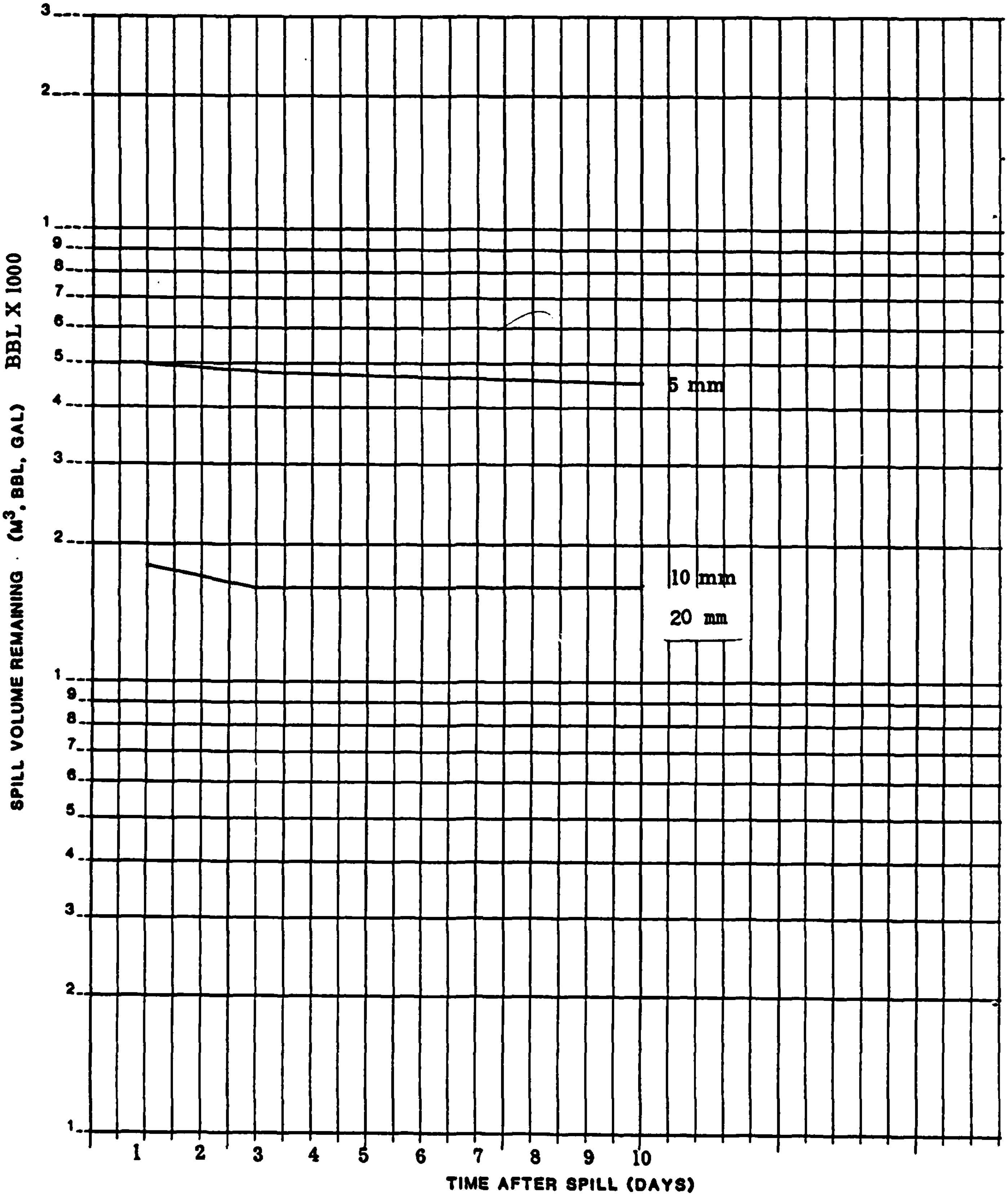
NOTE: Thickness would decrease with evaporation loss; area would remain about the same.

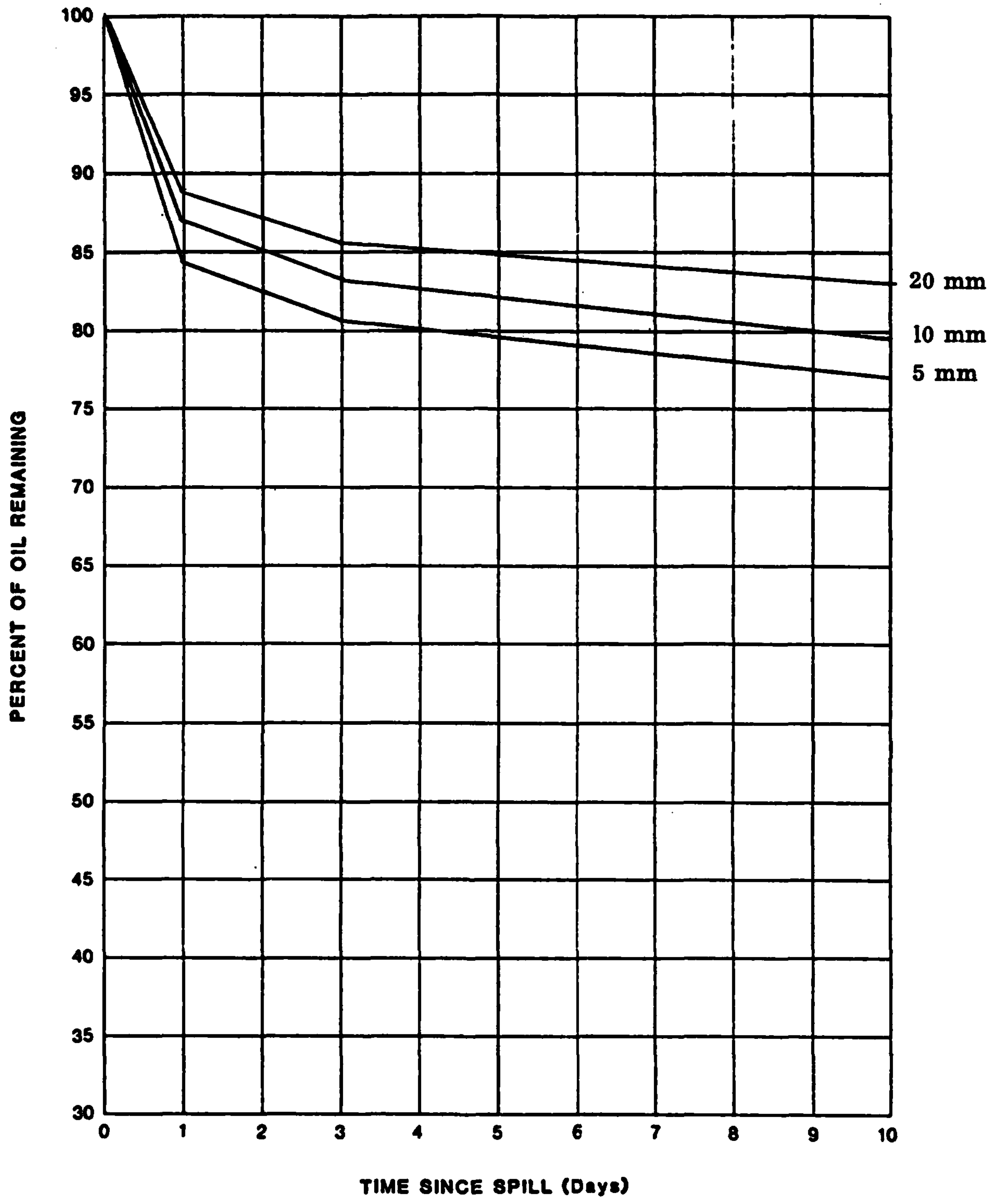
Day 10

Location	Thickness	Area	%Remaining	Volume
96 NM DOWN WIND, OR ON	5 mm	---	77	$7,300 m^3$ (46K bbl)
THE BEACH AT BARROW	10 mm	---	79	$2,500 m^3$ (16K bbl)
	20 mm	---	83	$2,600 m^3$ (17K bbl)
			TOTAL	79,000 bbl

SPILL BEHAVIOR WORK SHEET #4

SPILL VOLUME REMAINING





SPILL BEHAVIOR WORK SHEET #5

EVAPORATION RATE

SPILL BEHAVIOR WORK SHEET #6
SPREADING ON OPEN WATER
SCENARIO 6

		THICK SLICK		THIN SLICK
1)	SPILL RADIUS (m):	460 to 870 m		1,000 to 10,000 m
2)	SLICK THICKNESS (mm):	5 - 20 mm		0.005 mm
3)	SPILL DRIFT VECTOR:	AVERAGE 293°T/0.6 kts	RANGE	272°T/0.4 kts 325°T/0.2 kts

4) DISTANCE TO SHORELINE (NM): MAX 56 MIN 28

TIME TO REACH SHORELINE (HRS): MAX 5.8 days MIN 3 days

5) ESTIMATED TIME OF ARRIVAL AT SHORELINE: SOONEST ______ LATEST ______ Depends on breakup

6) LENGTH OF SHORELINE CONTAMINATED (NM): 23.5

LENGTH ACCORDING TO SPILL RETENTION INDEX (NM)

1		5	8.9
2		6	3.1
3	4.4	7	7.1
4		8	

ASSESSMENT OF IMPACT BASED ON SPILL RETENTION INDEX

- o SHORELINE TYPE 3) Non-veg. barrier island, 5) Lagoon-facing mainland shore, 6) Peat shore, 7) Sheltered tidal flats
- o IMPACT 3) Minimal, but could be transported offshore, 5) Low, but may enter other areas; 6) Serious effect on nutrient chain, 7) Absorbed in organic debris
- o PERSISTENCE 3) 1 year, 5) years, 6) years, 7) years
- o PROTECTION 3) Offshore boom, but probably could be left exposed, 5) to 7) Boom off lagoon entrance
- o CLEAN-UP 3) Small amount of oil could be left in place; remove large accumulation., 5) Clean to protect tundra margin, 6) Remove peat, 7) Clean tidal flats manually

7) DISTANCE TO PACK ICE (NM): 20 TIME TO REACH PACK ICE(HRS) MAX 6 days MIN 4.2 days

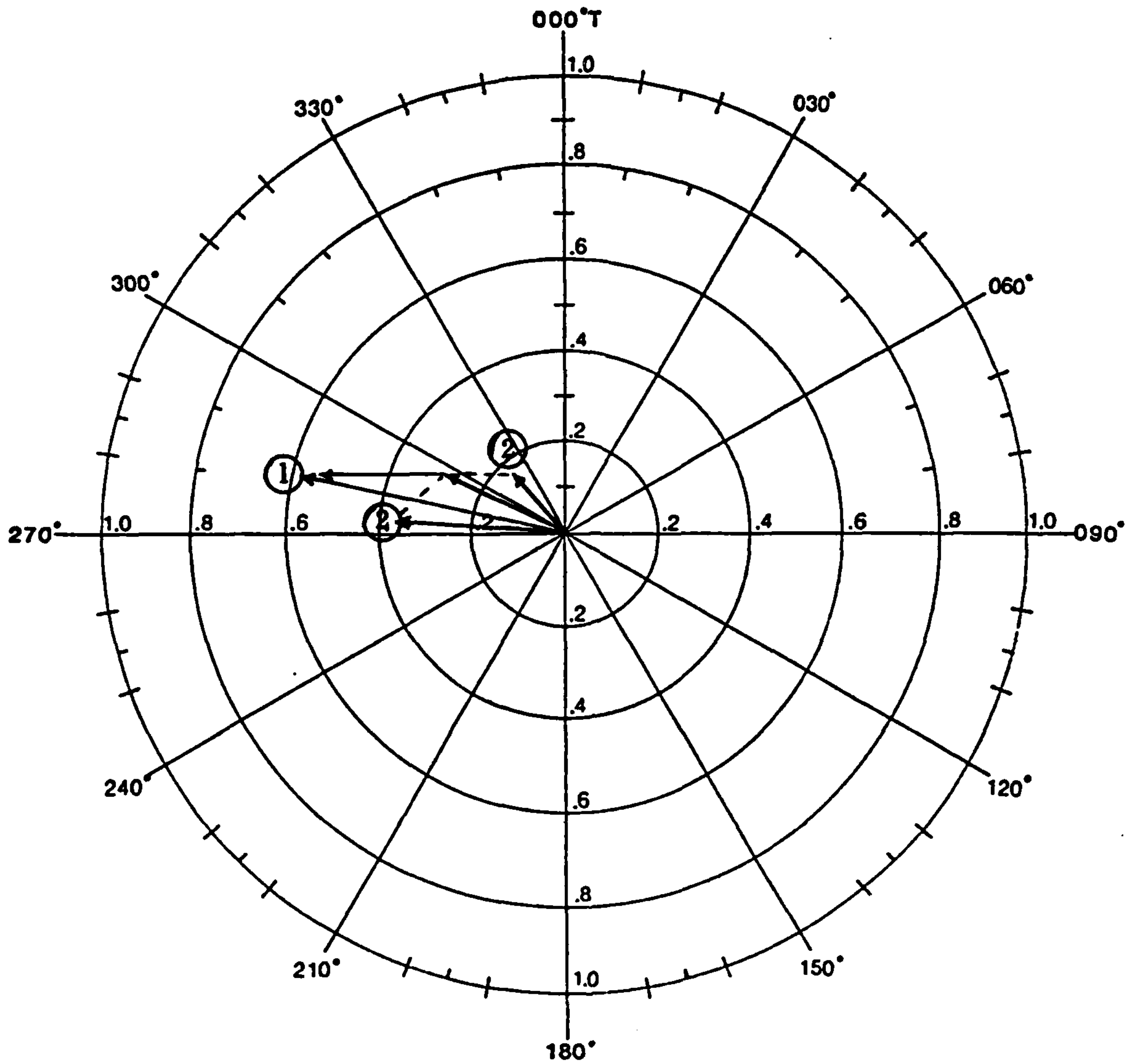
8) ESTIMATED TIME OF ARRIVAL AT PACK ICE: SOONEST --- LATEST ---

9) LENGTH OF PACK ICE CONTAMINATED (NM) Depends on point of arrival & drift

10) ESTIMATED DRIFT OF PACK ICE (NM/DAY) 6

SPILL BEHAVIOR WORK SHEET #7

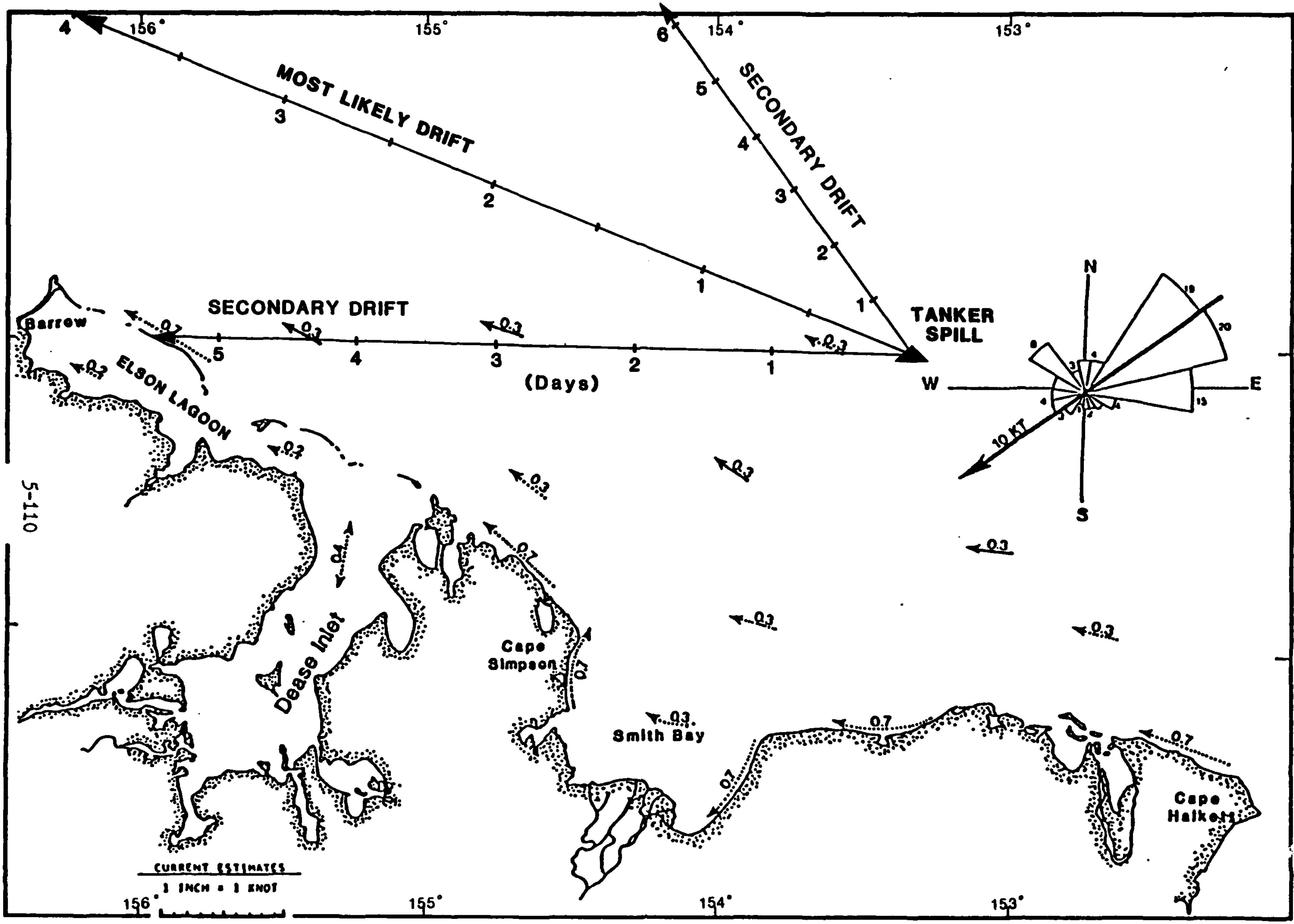
PLOT OF SPILL DRIFT



SCENARIO 6

1. Primary drift vector 293°T/0.6 kts

2. Secondary drift vectors 272°T/0.4 kts and 325°T/0.2 kts



CURRENT SPEEDS BASED ON FIELD MEASUREMENTS.
CURRENT SPEEDS EXTRAPOLATED FROM WINDS, MEASURED CURRENTS, MODEL RESULTS, ETC.
PROBABLE EDDY.

FIGURE 5.4.17 TANKER SPILL

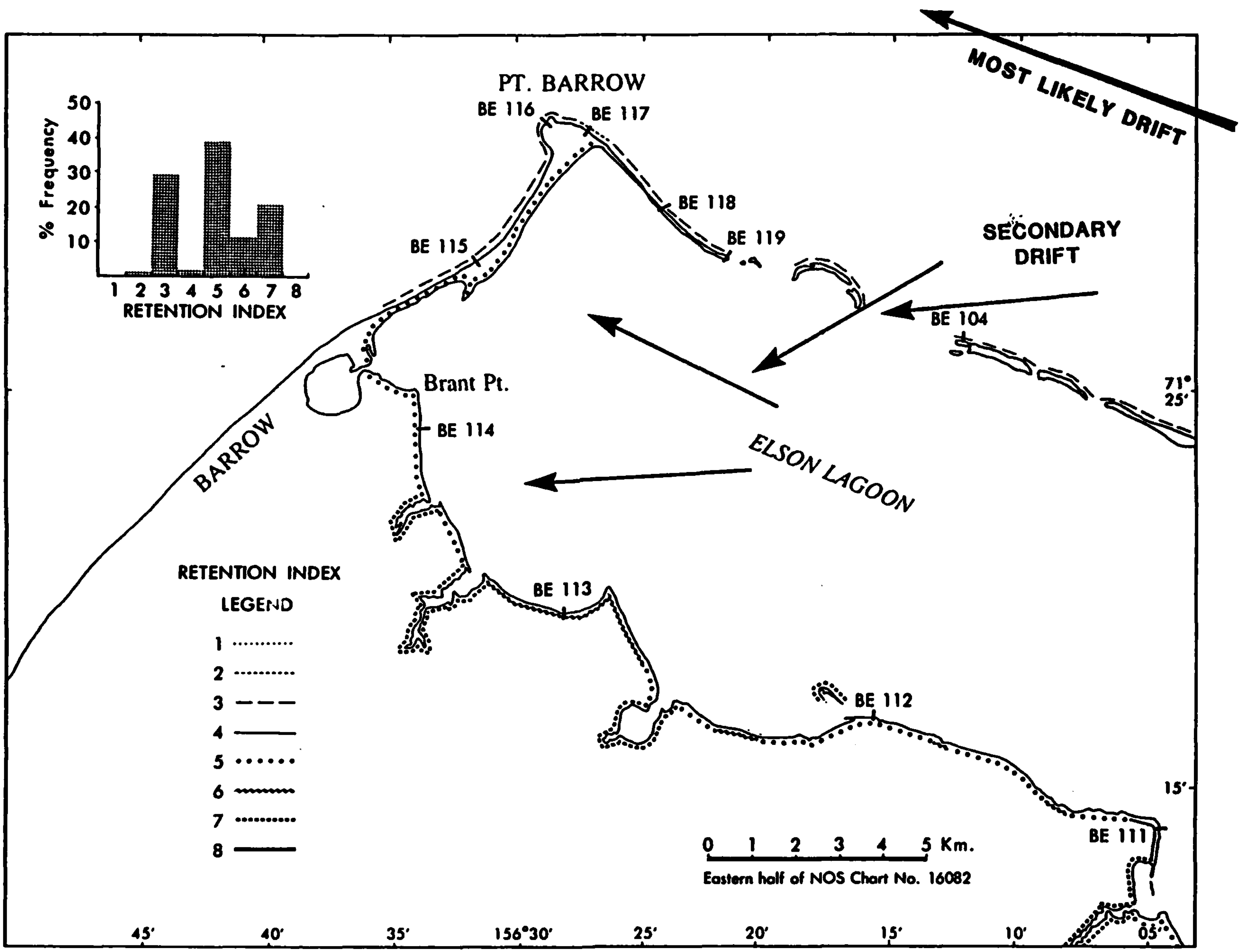


FIGURE 5.4.18 SPILL IMPACT AT BARROW

SCENARIO REFERENCES

1. Lissauer, Ivan, L. E. Hachmeister, B.J. Morson, and J.B. Vinelli, Atlas of the Beaufort Sea, U.S. Coast Guard Research and Development Center, Groton, Connecticut, January 1984.

2. LaBelle, J.C., J.L. Wise, R.P. Voelker, R.H. Schulze, and G.M. Wohl, Alaska Marne Ice Atlas, Arctic Environmental Information and Data Center, University of Alaska, Anchorage, Alaska, 1983.

3. Barnes, Peter W., Erk Reimnitz, Lawrence J. Toimil, and Harry R. Hill, Fast Ice Thickness and Snow Depth Relationships Related to Oil Entrapment Potential, Prudhoe Bay, Alaska, in the Proceedings of the Fifth International Conference on Port and Ocean Engineering Under Arctic Conditions POAC, The University of Trondheim, Norway, August 1979.

4. NORCOR Engineering and Research, Limited, The Interaction of Crude Oil With Arctic Sea Ice, Beaufort Sea Technical Report #27, Beaufort Sea Project, Department of the Environment, Victoria, B.C., December 1975.

5. S.L. Ross Environmental Research Ltd., A Review of Countermeasures for a Major Oil Spill From a Vessel in Arctic Waters, Environment Canada report EPS 3-EC-83-2, Environmental Protection Service, Environment Canada, March 1983.

APPENDIX A

COMMONLY USED ICE TERMS

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APPENDIX A

COMMONLY USED ICE TERMS

1. Natural Ice Types

   - Smooth ice - any area of sea ice that has not been affected by ice deformation mechanisms. Also referred to as sheet ice.

   - Deformed ice - the antithesis of smooth ice.

   - First-year ice - sea ice that is less than one year old.

     - Nilas - ice less than 10 cm (four inches) thick. Nilas can be distinguished visually from aerial reconnaissance or remote imagery as dark areas.

     - Young ice - ice from 10-30 cm (4-12 inches) thick. Young ice can be distinquished visually from aerial reconnaissance or remote imagery as gray areas.

     - Granular - ice with small granular crystals. The presence of thick granular ice is often accompanied by the presence of sediment and other foreign material trapped in the ice.

     - Columnar/random - columnar-grained ice with c-axes oriented in random horizontal directions. (c-axis is the principal crystallographic axis of an ice crystal.)

     - Columnar/ oriented - columnar-grained ice with c-axes oriented in a preferred horizontal direction.

   - Multi-year ice - sea ice that has survived one or more melt seasons.

   - Ice island ice - ice of ice shelf origin.

2. Zones

   - Fast ice zone - any type of sea ice that is attached to a shoreline (sometimes called landfast) or grounded ice feature.

   - Pack ice - any area of sea ice other than fast ice.

   - Transition zone(s) - the zone, usually heavily deformed, that may exist between fast ice and pack ice. The width of this zone may be up to tens of miles depending on seasonal and annual changes. Fast ice may be found in this zone adjacent to grounded features. Often referred to as Stamukhi zone, or shear zone, which is misleading

because the mechanism of deformation is not necessarily shear.

- Active zone - a zone in which ice is deforming.

- Arctic pack - pack ice consisting primarily of multi-year ice in constant motion.

3. Openings

- Open lead - an essentially linear, wet opening in sea ice of navigable width.

- Crack - a non-navigable fracture in the ice.

- Refrozen lead - a lead in which ice has grown, but remains relatively smooth. Thickness can vary from a few inches to several feet.

- Polynya - an areal opening in sea ice which may be open water or refrozen.

- Slot - a manmade cut in an ice sheet. May be wet (completely through the ice), partially refrozen, or dry (partially through the ice.)

4. Linear Features

- First-year ridges - linear ice feature of broken ice blocks created by pressure. Can be further subdivided as a shear ridge or compression ridge:

  - Shear ridge - first-year ridge formed by relative motion of two ice features in direction primarily parallel to their common boundary. Sufficient compression must be maintained to keep the two features in contact. A shear ridge is composed of ground up ice chips, water-soaked and refrozen; usually a straightline feature with a vertical face.

  - Compression ridge - first-year ridge formed by buckling, bending, or local crushing of colliding ice features with relative motion in direction primarily perpendicular to their common boundary. Generally composed of loosely stacked angular ice blocks, a compression ridge tends to be a curvilinear feature with sloping sides.

- Multi-year ridge - a ridge that has survived one or more summer melt seasons.

- Ridge sail - portion of an ice ridge that extends above the water line.

- Ridge keel - portion of an ice ridge that extends below the water line.

- Finger rafting - rafted ice in which two sheets alternately overide each other along their common boundary. Predominant feature of thin ice sheets, and can be identified with most first-year compression ridges.

5. Areal Features

- Floes - relatively flat areal ice feature surrounded by distinquishable boundaries.

- Rafted ice - ice consisting of two or more ice sheets layered as a result of overriding.

- Rubble pile - ice feature of areal, rather than linear, extent created by ice breaking against a grounded feature. A rubble pile may consist of one or more pileups.

- Rubble field - floating or grounded ice feature composed of broken ice pieces refrozen in a contiguous feature of areal extent large with respect to its height.

- Multi-year floe - an ice floe that has survived one or more melt seasons.

- Artificial ice island - a grounded mass of predominantly constructed ice.

- Natural ice island - tabular, fresh-water fragments from high latitude arctic ice shelves.

- Floating ice platform - a floating mass of constructed and/or natural ice that is used as a working surface.

6. Feature Characteristics

- Porosity - property to indicate the ratio of the volume of voids to the total volume of an ice feature where voids can be air, snow, or water.

- Consolidation - process of solidification of an ice feature due to freezing of water in voids between ice blocks, pore water, or melt water.

- Sintering - process of bonding of ice blocks due to pressure where the voids are either air or snow.

Note: This Appendix is an abbreviated list taken from AOGA Ice Engineering Nomenclature, Lease Sale Planning and Research Committee, Alaska Oil and Gas Association, January 1981.

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